Studies of Single Top Quark Production at the Tevatron

Matteo Cremonesi
on behalf of the **CDF** & **D0** Collaborations

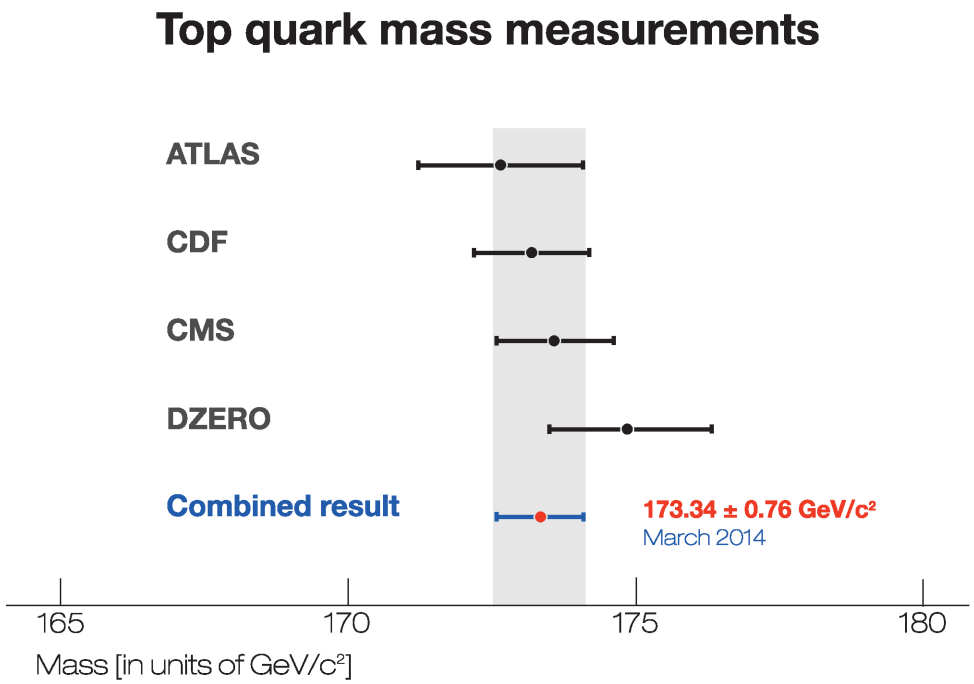
The Top Quark

Heaviest known elementary particle:

- Latest **world combination**: 173.34 ± 0.76 GeV/c^2

Short lifetime:

- No hadronization, it decays
  - Nearly 100% of the times in a W boson and in a b quark
- Opportunity to study a *bare quark*



Single Top Quark Production

Observed by CDF and D0 in 2009

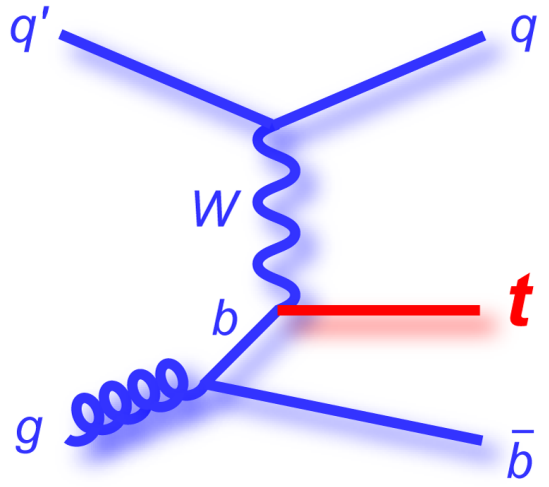
- Direct measurement of the $|V_{tb}|$ CKM matrix element
- Sensitive to new physics

t-channel: $\sigma_t \cong$ 2 pb; **$S/B \cong$ 0.05**

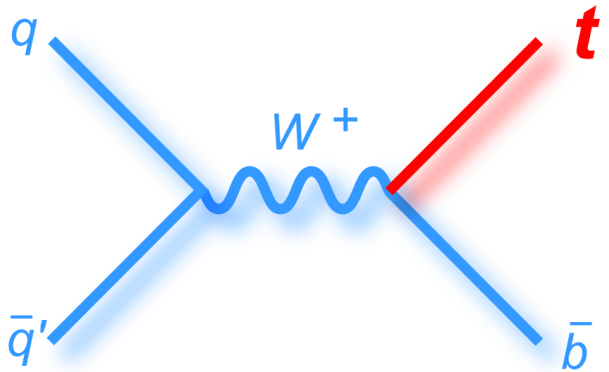
- Powerful discriminating features
- Both Tevatron and LHC are sensitive to t-channel

s-channel: $\sigma_s \cong$ 1 pb; **$S/B \cong$ 0.03**

- Less separation with respect to the background
- More difficult at LHC
  - 5 times more signal, 15 times more background

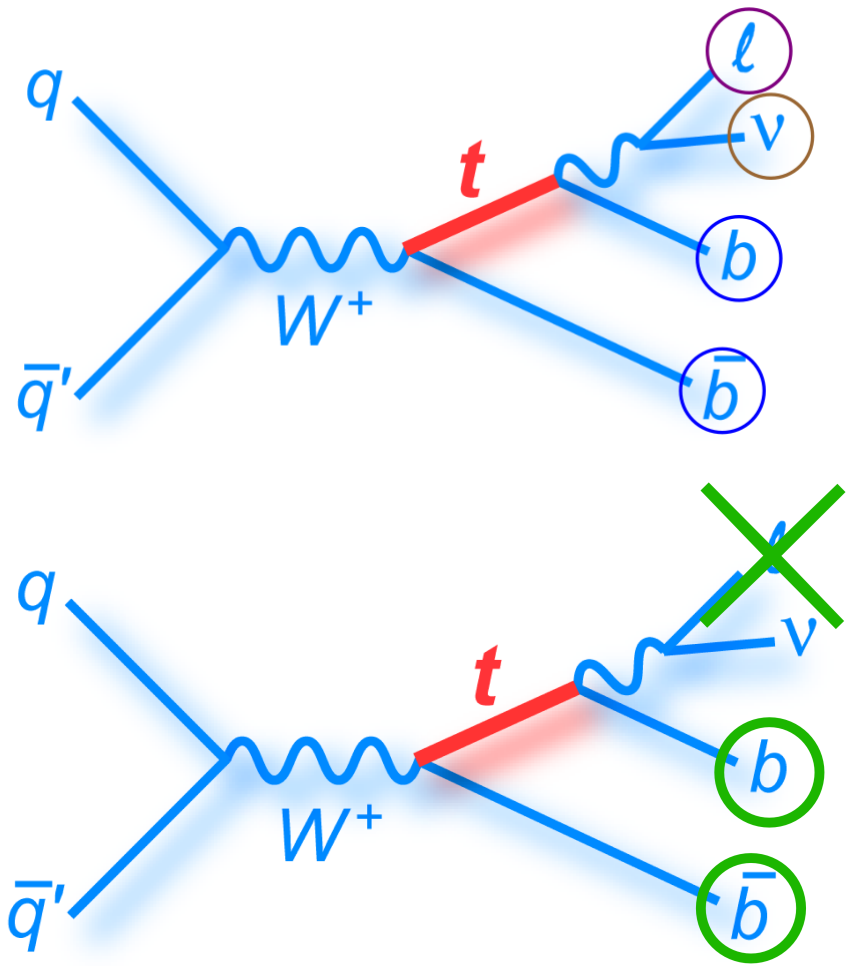


t-channel



s-channel

Event Selection



$\ell\nu b\bar{b}$:

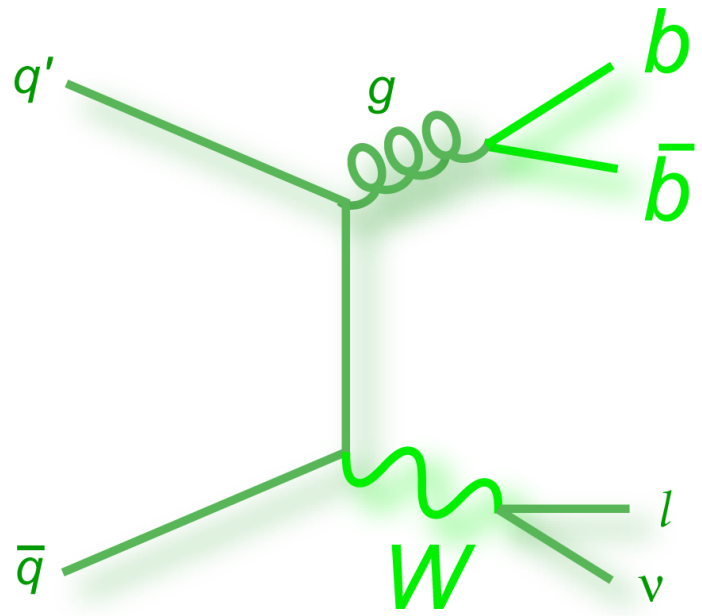
- One high p_T isolated lepton (e,μ)
- Missing transverse energy ($\not\!\!E_T$)
- Two or more jets
- At least one b-tag

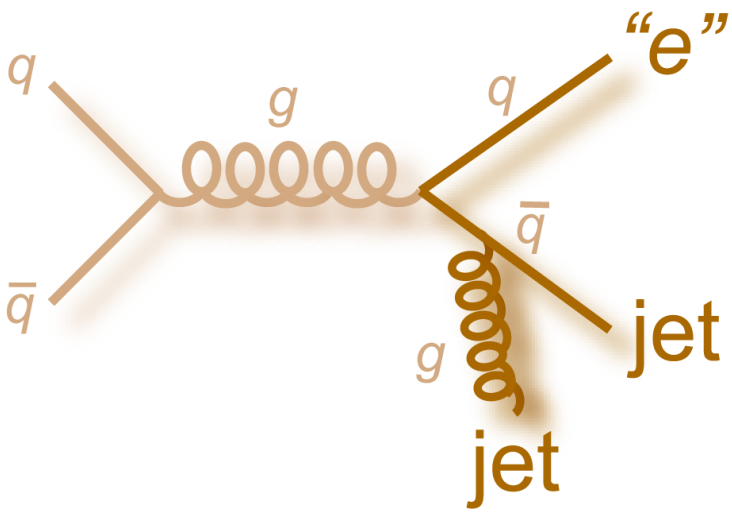
$\not\!\!E_T b\bar{b}$ (CDF only!):

- No isolated leptons (e,μ)
  - Leptons are explicitly vetoed
  - Orthogonal to $\ell\nu b\bar{b}$ sample
- Large $\not\!\!E_T$:
- Two or more jets
- At least one b-tag

$\Rightarrow$ It adds 33% of acceptance to the $\ell\nu b\bar{b}$ selection

Signal and Background Model





Electroweak/Top: single top, diboson, and $t\bar{t}$:

- modeled by Monte Carlo (MC)
  - single top: POWHEG (CDF), COMPHEP (D0)
  - $t\bar{t}$, diboson, WH/ZH: PYTHIA
- MC normalized to theoretical cross-section

***W*+Heavy Flavor**:

- modeled by ALPGEN
- normalization from data

Mistags: falsely tagged light quark or gluon jets

- mistag probability from data

QCD multijet: Data-derived model

CDF $\ell\nu b\bar{b}$ Event Yield

Category	TT+TL	1T+LL
$t\bar{t}$	357 ± 40	560 ± 57
Diboson	58.7 ± 7.8	279 ± 34
Higgs	12.5 ± 1.0	12.0 ± 0.9
Z+jets	31.6 ± 3.5	190 ± 21
QCD	76 ± 31	326 ± 130
W+HF	712 ± 286	2597 ± 1046
W+LF	66 ± 14	1220 ± 175
t-channel	53.4 ± 6.7	265 ± 30
s-channel	116 ± 12	127 ± 12
Total	1484 ± 403	5574 ± 1501
Data	1231	5338

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CDF $\ell\nu b\bar{b}$ Event Yield

The background uncertainty is larger than the predicted signal, cannot do a simple counting experiment
$\Rightarrow$ **Make use of multivariate techniques**

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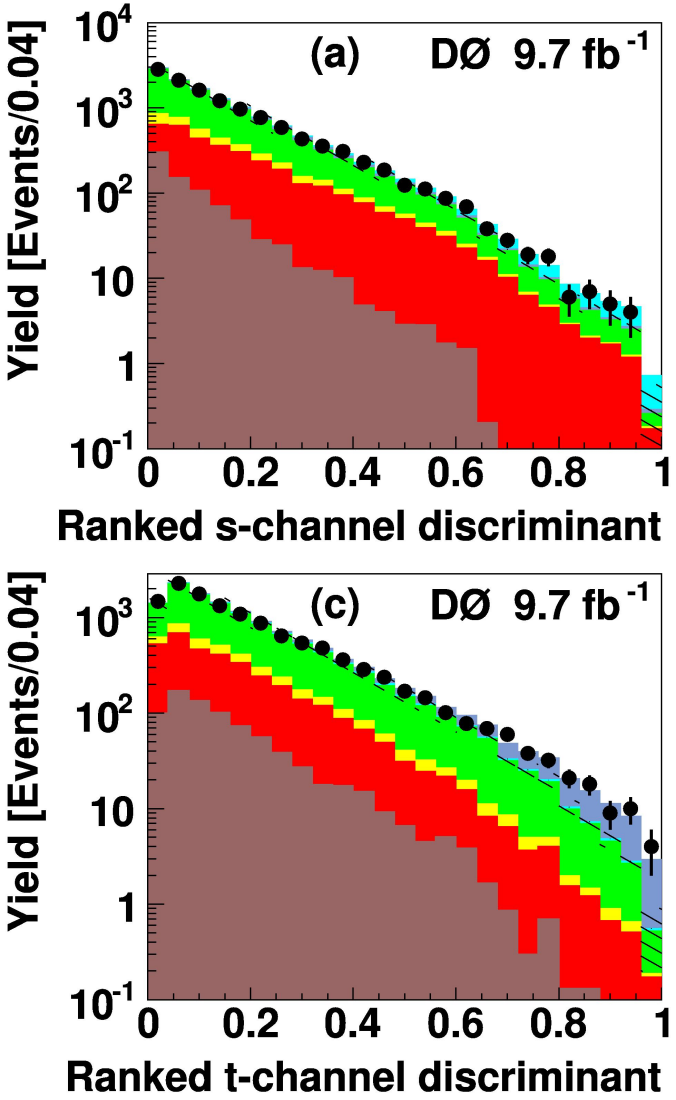
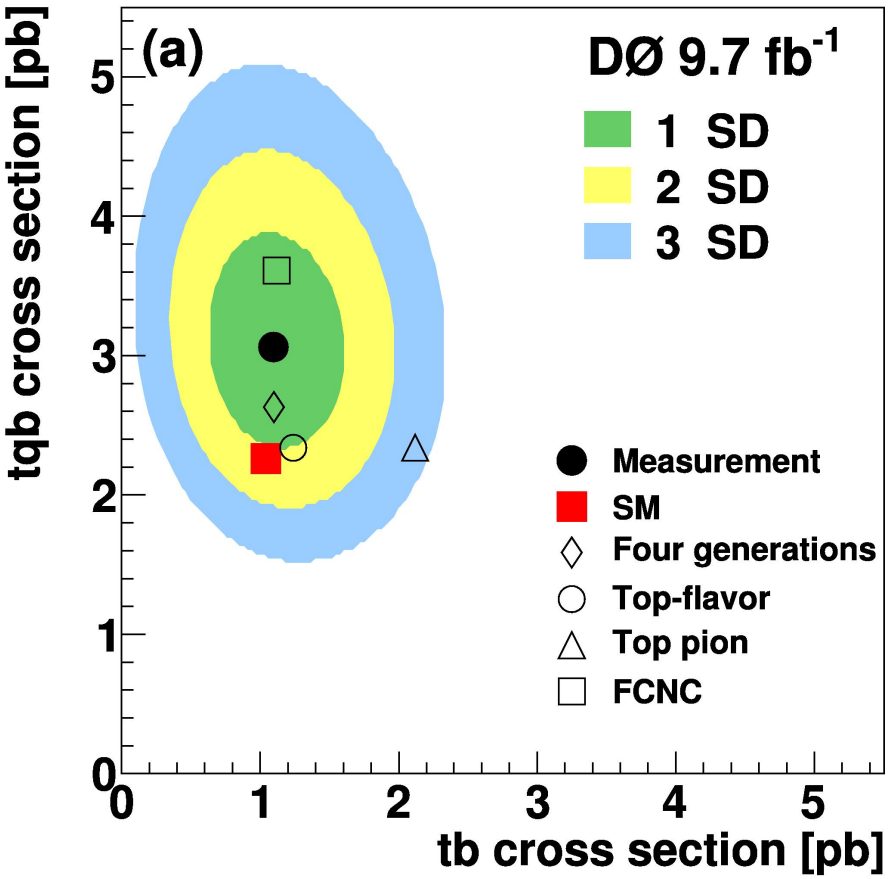
D0 Analysis



Strategy:

- Full D0 dataset (9.7 fb^{-1})
- Combination of boosted decision trees, Matrix elements and neural networks in a Bayesian neural network
- 2D final discriminant sensitive to both s- and t-channel
- 1D posterior for σ_{s+t} integrating over σ_t, without assuming the SM σ_s/σ_t
- Integrate over σ_t and extract σ_s and viceversa

D0 Analysis



Phys. Lett. B 726, 656 (2013)

Results:

- Cross sections:
  - $\sigma_s = 1.10^{+0.33}_{-0.31}$ (stat+syst) pb
  - $\sigma_t = 3.07^{+0.53}_{-0.49}$ (stat+syst) pb
  - $\sigma_{s+t} = 4.11^{+0.59}_{-0.55}$ (stat+syst) pb
- p-values:
  - s-channel: 3.7σ (3.7σ expected) **first evidence of s-channel**
  - t-channel: 7.7σ (6.0σ expected)
- $|V_{tb}| > 0.92$ at 95% C.L.

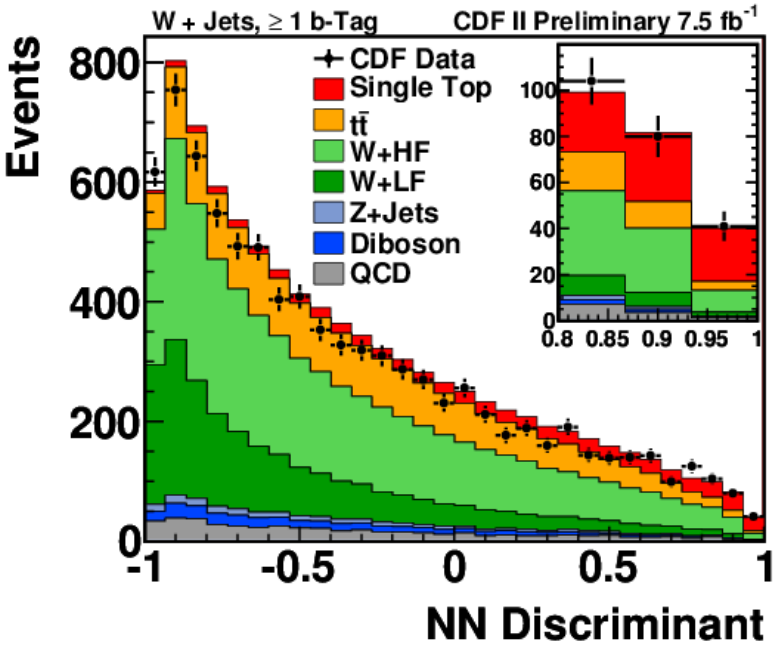
CDF $l\nu b\bar{b}$ Analysis

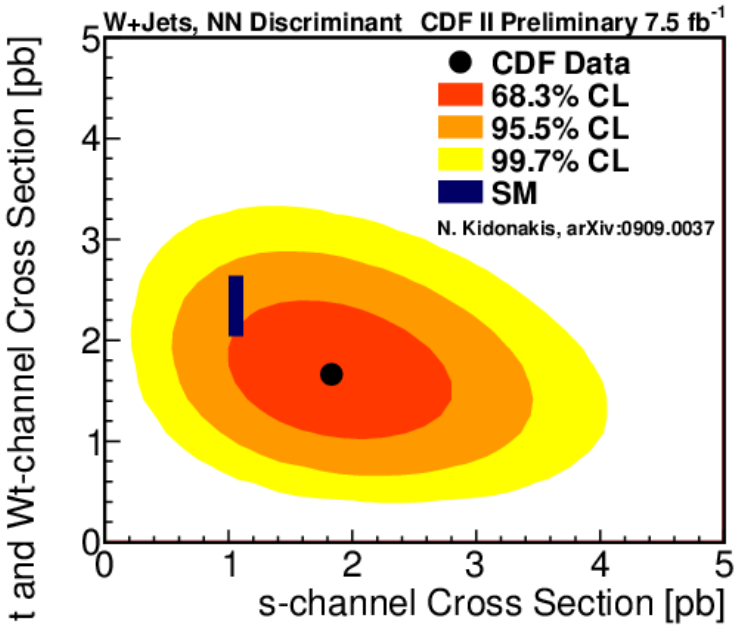
Strategy:

- 7.5 fb^{-1} of CDF data are analyzed
- 1D MVA discriminant sensitive to s/t-channel used in double/single tag
- 1D posterior obtained for σ_{s+t} assuming the SM σ_s/σ_t

Results:

- $\sigma_{s+t} = 3.04^{+0.57}_{-0.53}$ (stat+syst) pb
- $|V_{tb}| = 0.96 \pm 0.09$ (stat+syst)$\pm$0.05 (th)
- Limit: $|V_{tb}| > 0.78$ at 95% C.L.





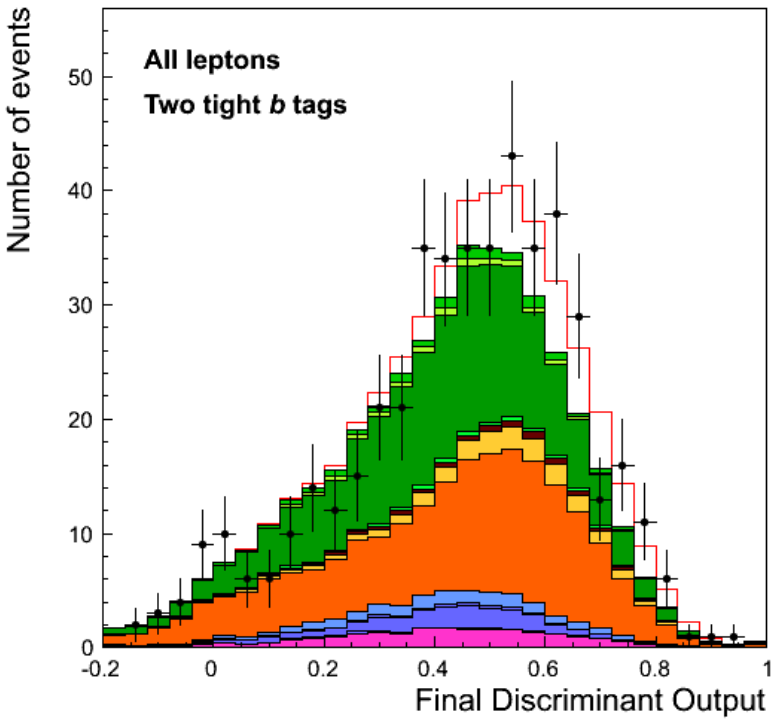
CDF $l\nu b\bar{b}$ s-channel Analysis

Strategy:

- Full CDF dataset (9.5 fb^{-1})
- 1D MVA discriminant sensitive to s-channel only
- t-channel included as background, constrained to the theoretical prediction
- New CDF HOBIT multivariate tagger is used

Results:

- $\sigma_s = 1.41^{+0.44}_{-0.42}$ (stat+syst) pb
- p-value $= 3.8\sigma$ (2.9σ expected)



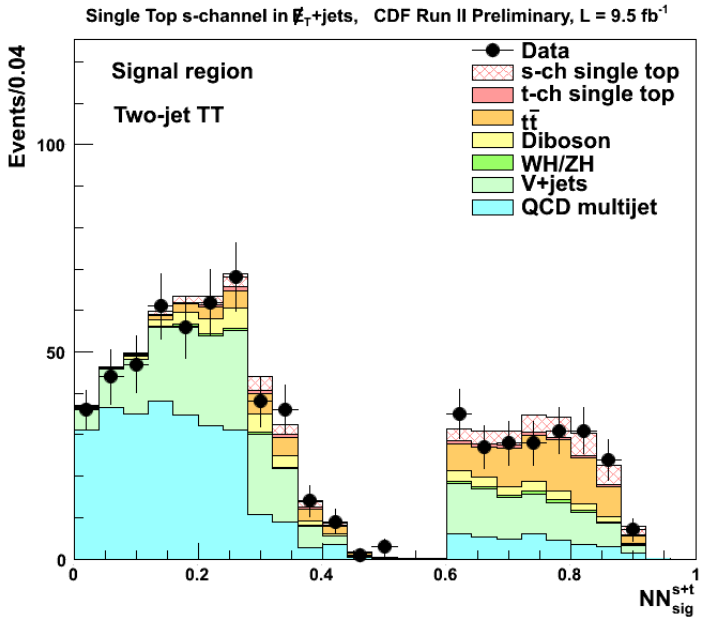
CDF $\not\!\!E_T b\bar{b}$ Analysis

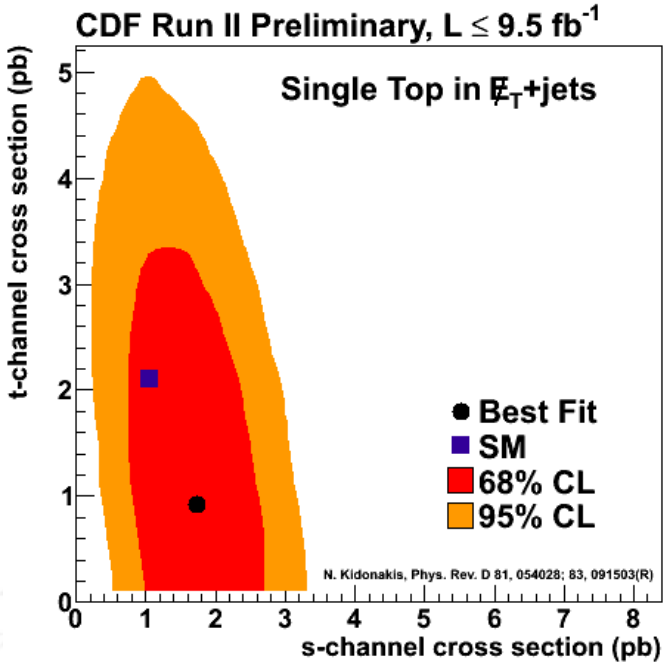
Strategy:

- Full CDF dataset (9.5 fb^{-1})
- 1D MVA discriminant sensitive to both s- and t-channel:
  - Combination of two s-/t-channel optimized MVAs
- 1D posterior obtained for σ_{s+t} assuming the SM σ_s/σ_t
- New CDF HOBIT multivariate tagger is used

Results:

- $\sigma_{s+t} = 3.53^{+1.25}_{-1.16}$ (stat+syst) pb
- $|V_{tb}| > 0.63$ at 95% C.L.





CDF $\not\!\!E_T b\bar{b}$ s-channel Analysis

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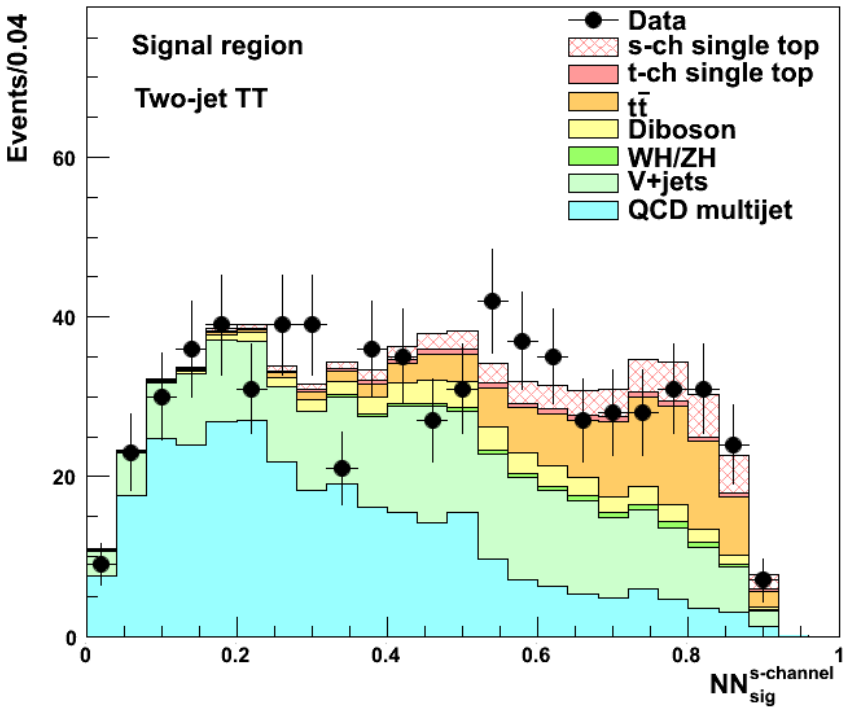


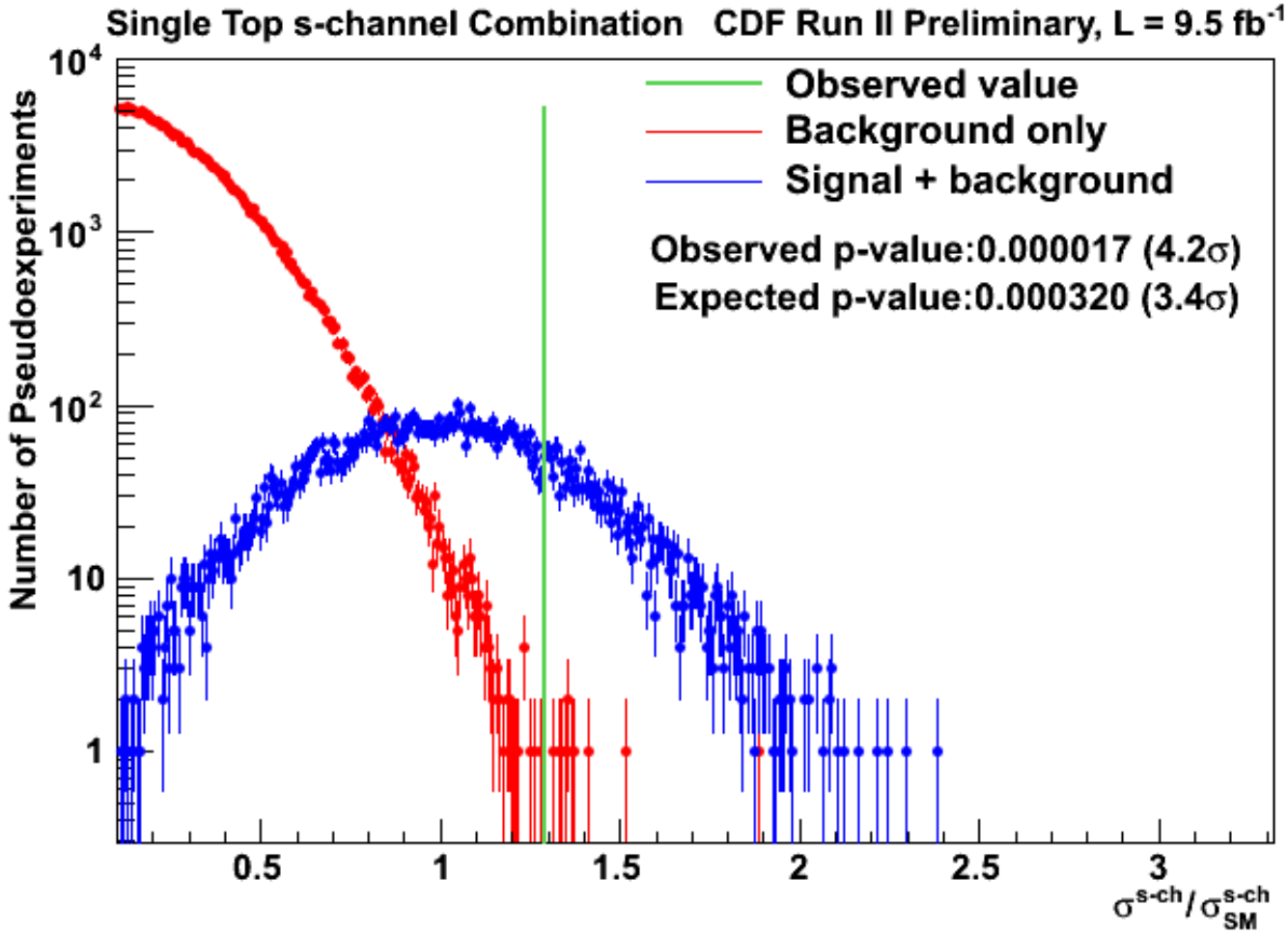
Results:

- $\sigma_s = 1.12^{+0.61}_{-0.57}$ (stat+syst) pb
- 1.9σ (1.8σ expected)

arXiv:1402.3756

CDF *s*-channel Combination

$$\sigma_s = 1.36^{+0.37}_{-0.32}\ \text{(stat+syst) pb}$$

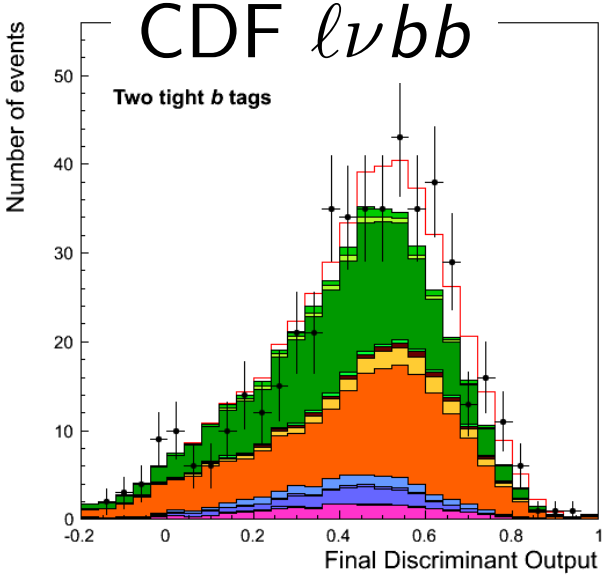


arXiv:1402.3756

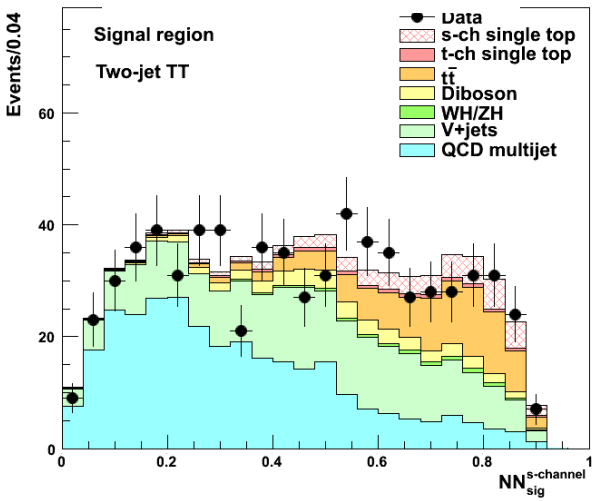
Tevatron *s*-channel Combination

Combination Inputs/Output

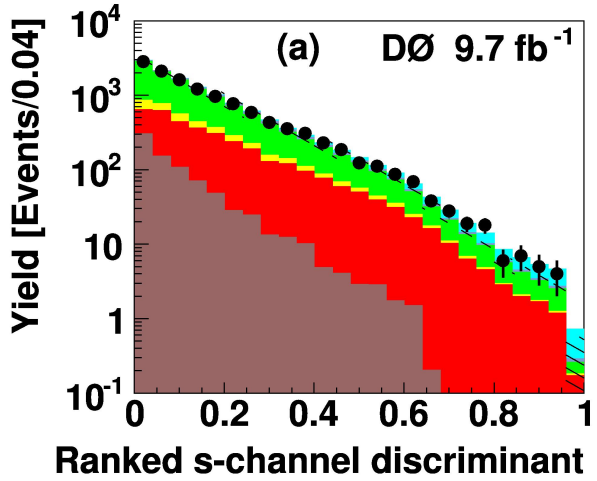
CDF $\ell\nu b\bar{b}$

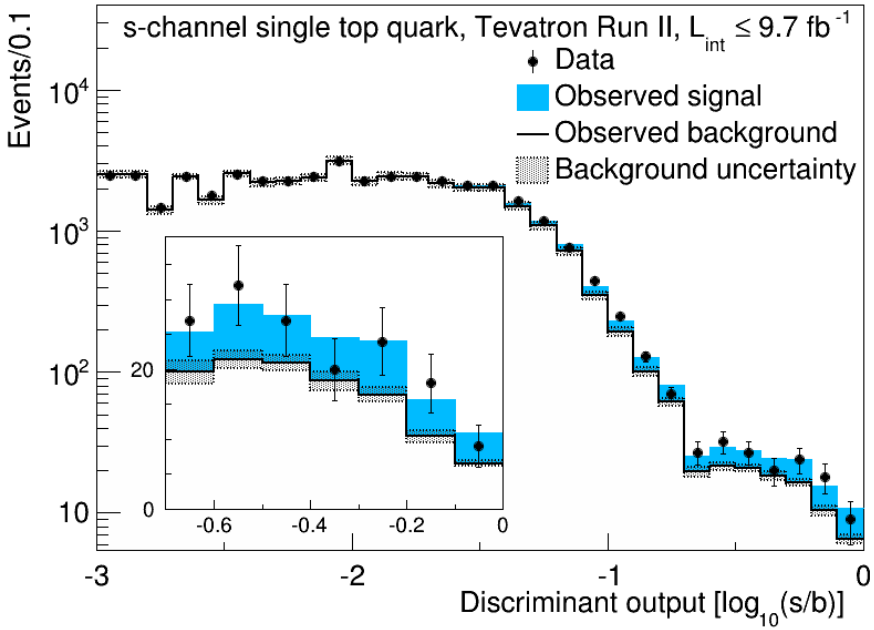


CDF $\not\!\!E_T b\bar{b}$

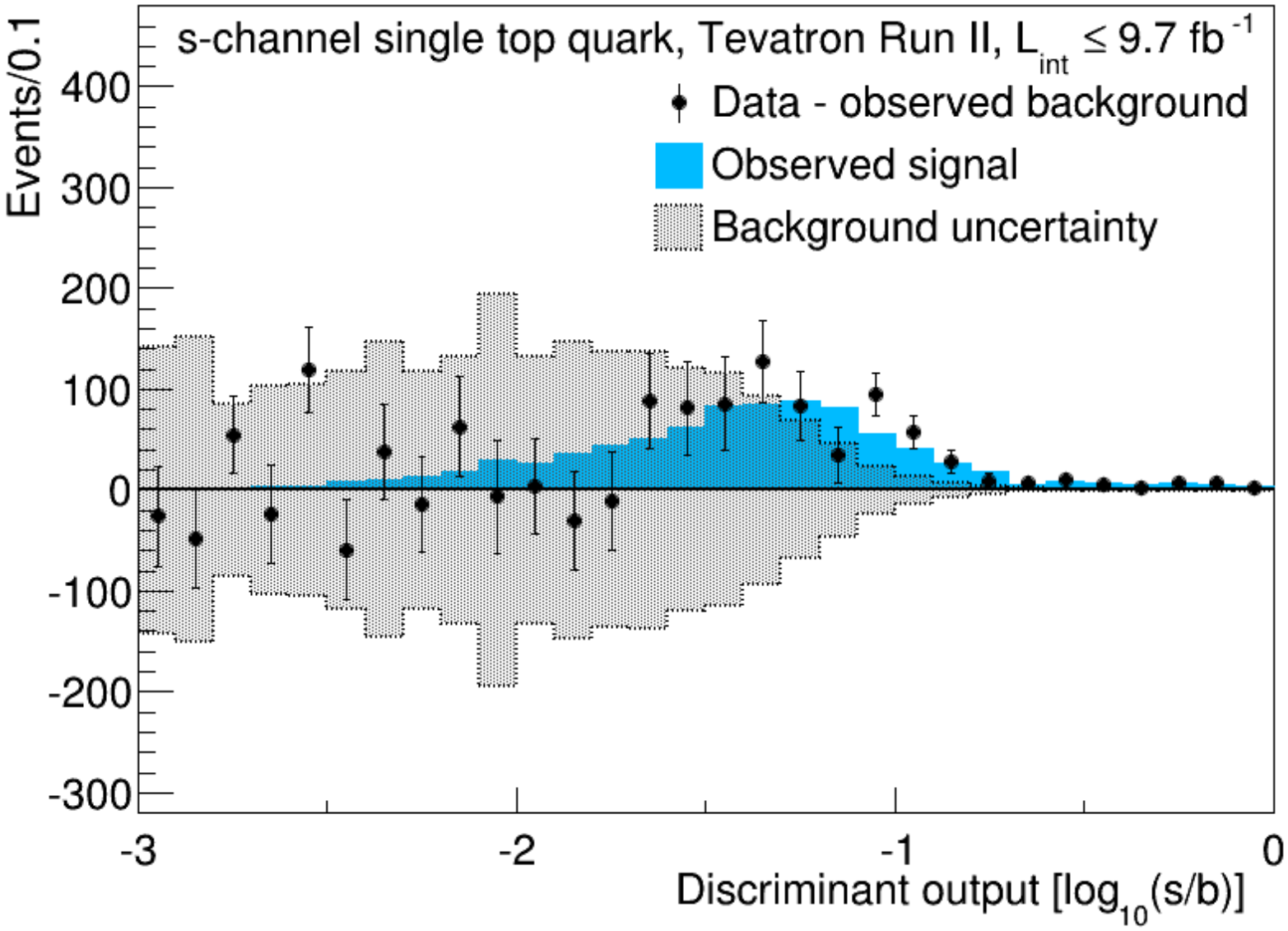


D0 $\ell\nu b\bar{b}$

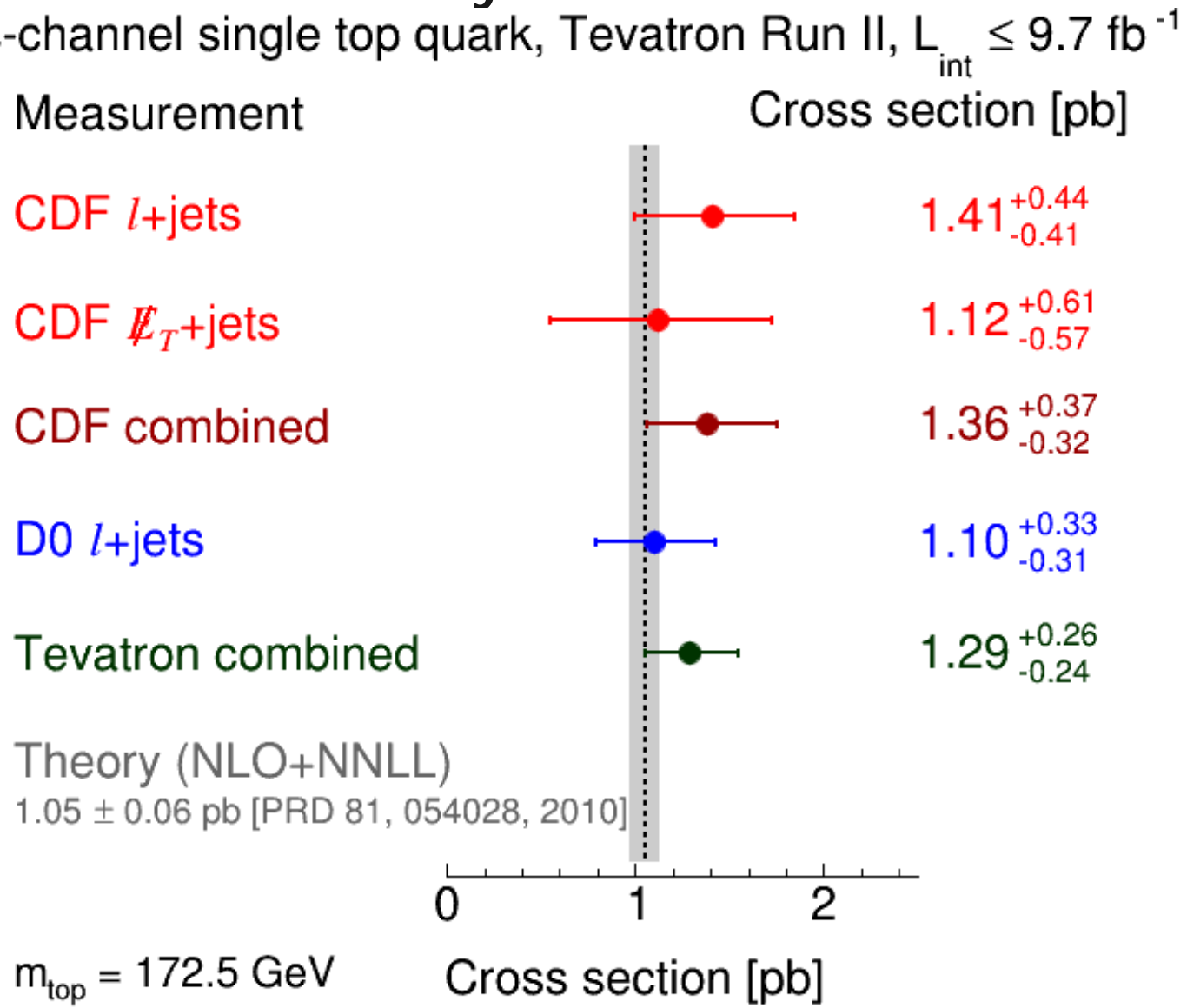




Background-subtracted Discriminant



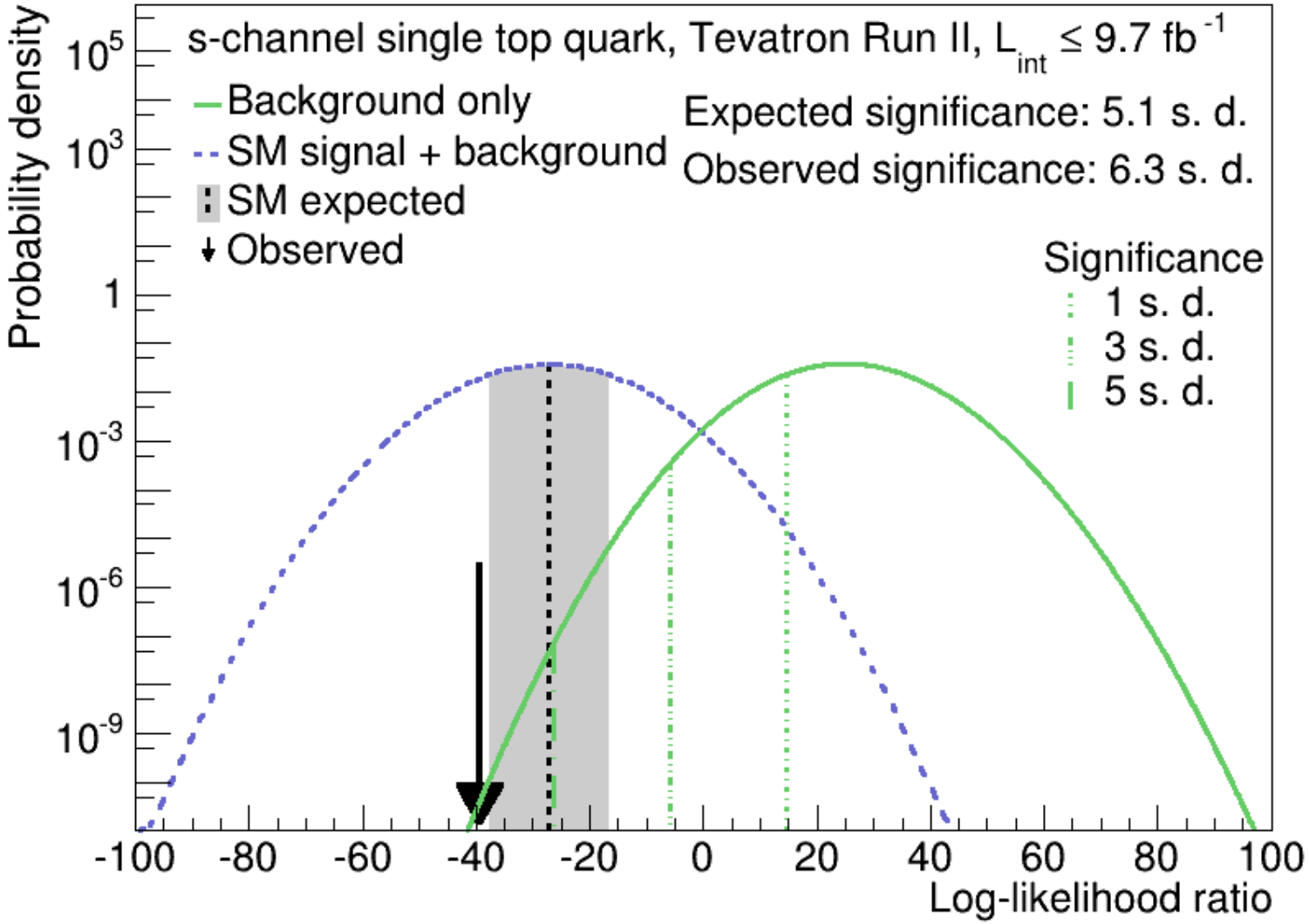
Cross Section Summary



- Equal contributions from CDF and D0
- Negligible top mass dependence

Tevatron Combined Significance

- LHC-style asymptotic approximation log-likelihood ratio
  - Reproduces ensemble-based significance estimate
- Observed p-value: 1.8×10^{-10}



Conclusions

Tevatron single top program is almost complete

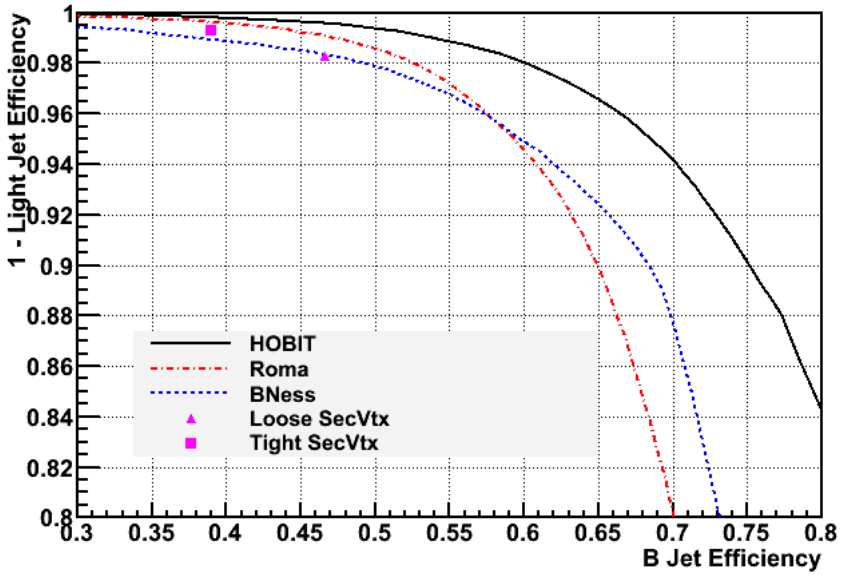
- Single top first observation in 2009
- t-channel first observation in 2011
- **s-channel first observation in 2014**
  - First Tevatron-combined observation of a new process, a unique case in HEP
  - Submitted to PRL, **arXiv:1402.5126**

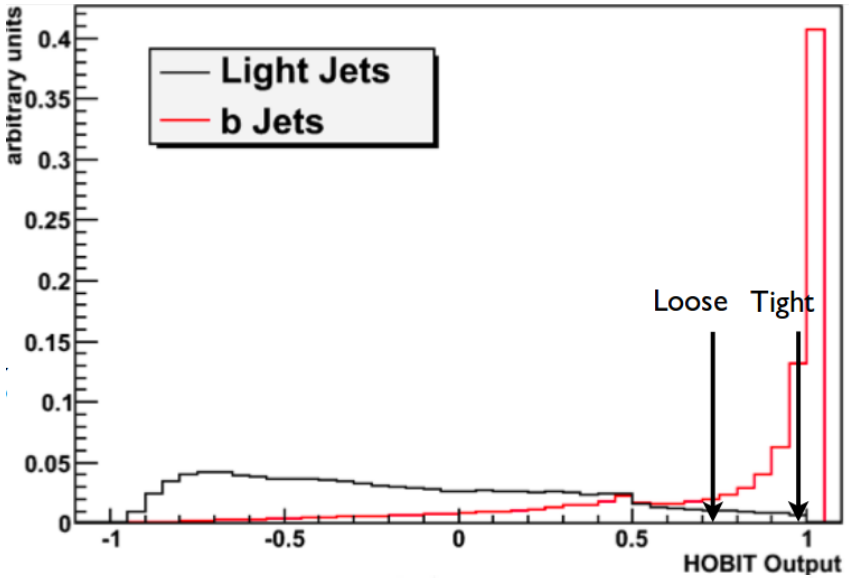
Final Tevatron combination coming soon

- Expected updates on V_{tb}, σ_{s+t}, and s-channel vs t-channel

Backup

HOBIT



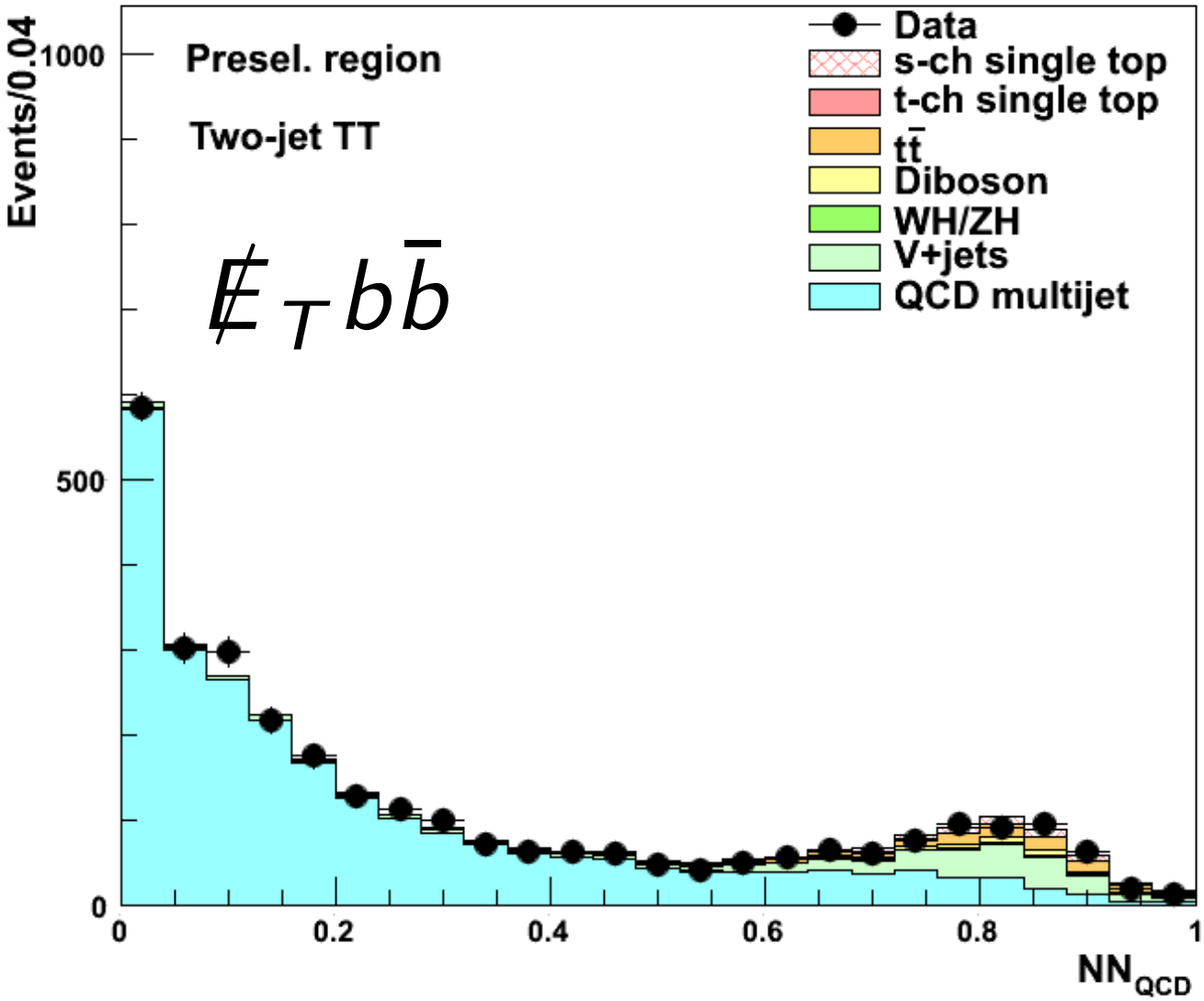


A new b-jet identification algorithm optimized for $H \to b\bar{b}$ searches is employed: **HOBIT**

- Incorporates all the features of the previous CDF b-taggers
- Two different HOBIT cuts are used: tight b-tag (T), loose b-tag (L)

Background Rejection

In the $\not\!\!E_T b\bar{b}$ analysis, QCD multijet production is by far the largest background with largest uncertainties



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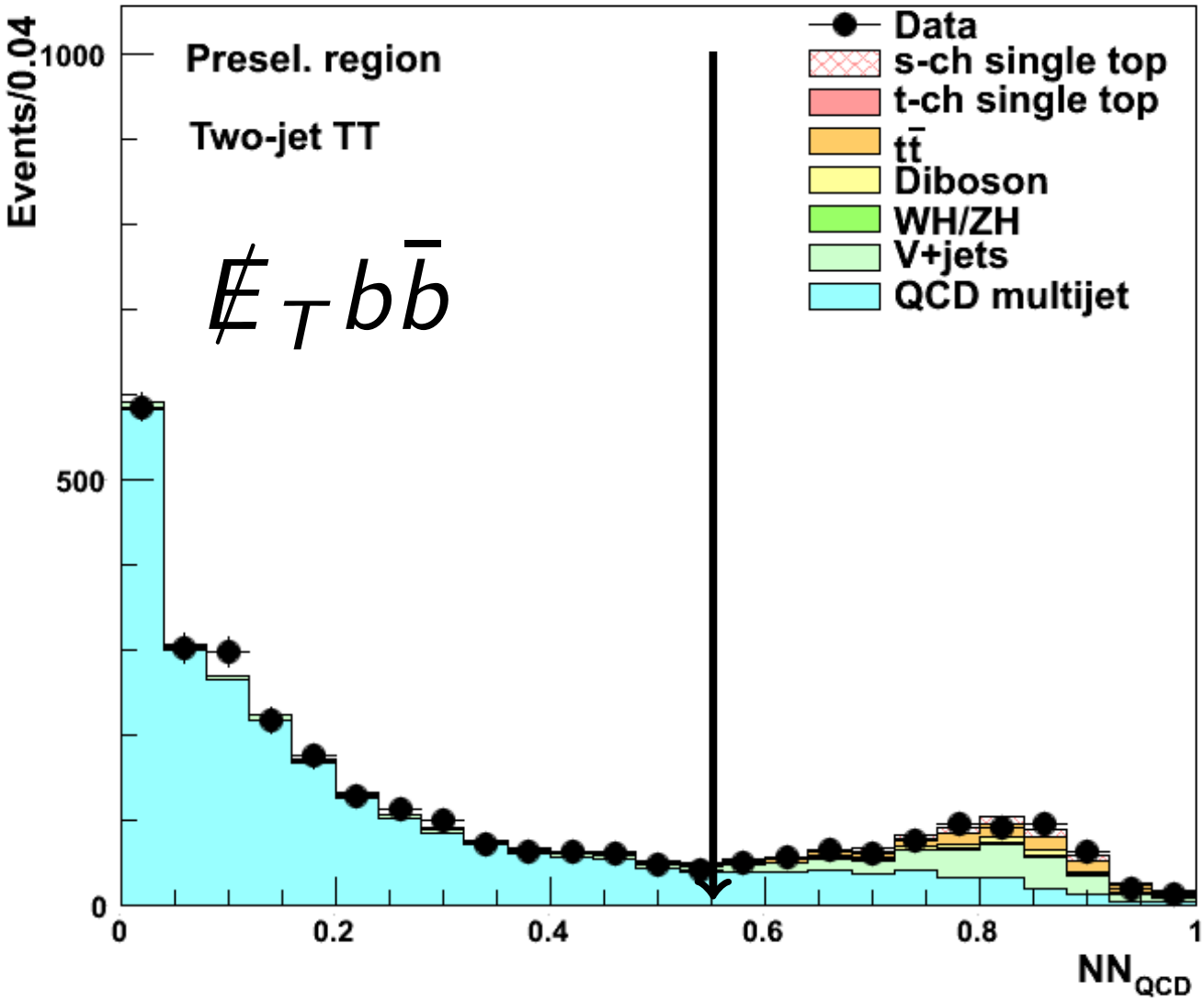

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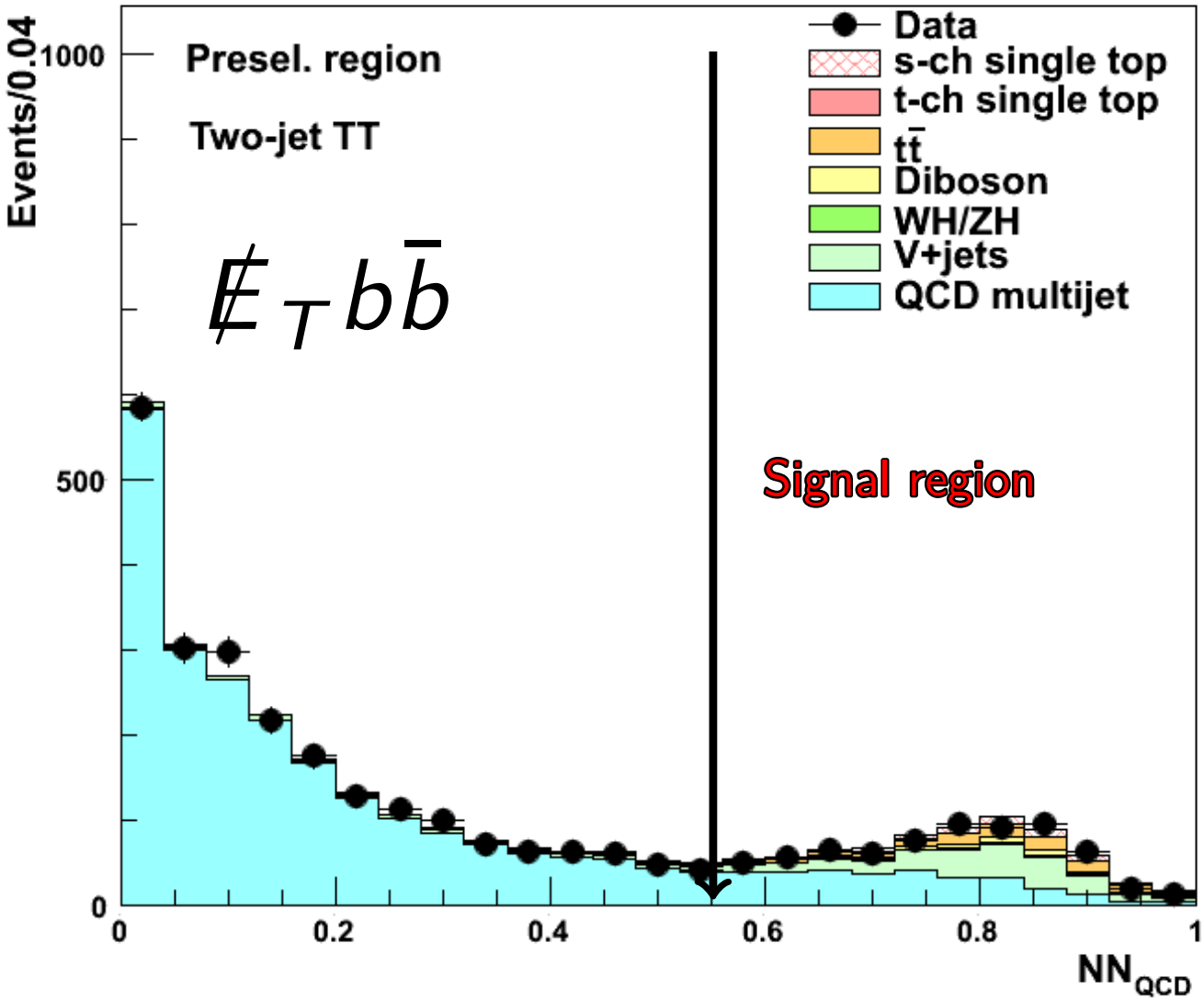

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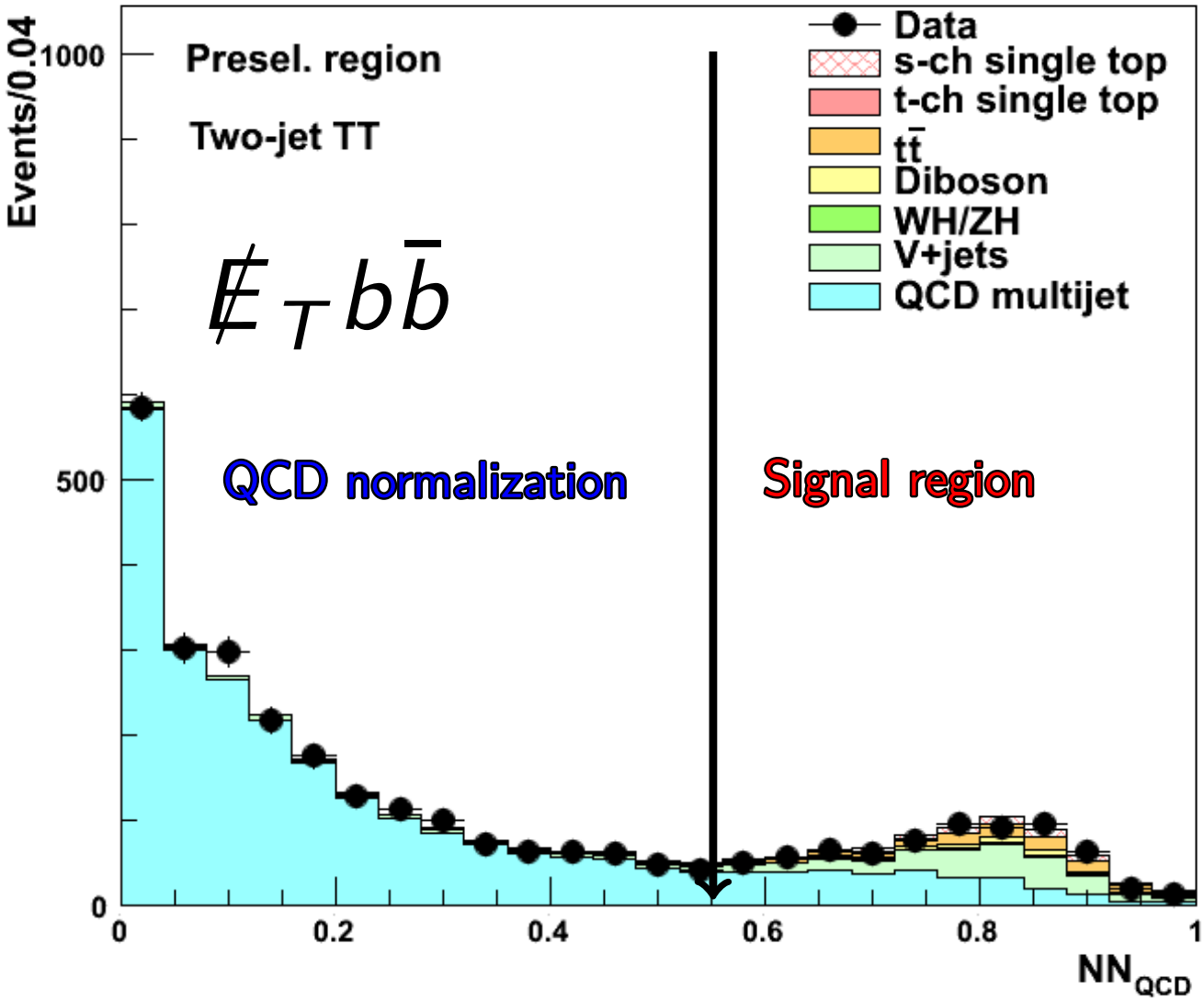

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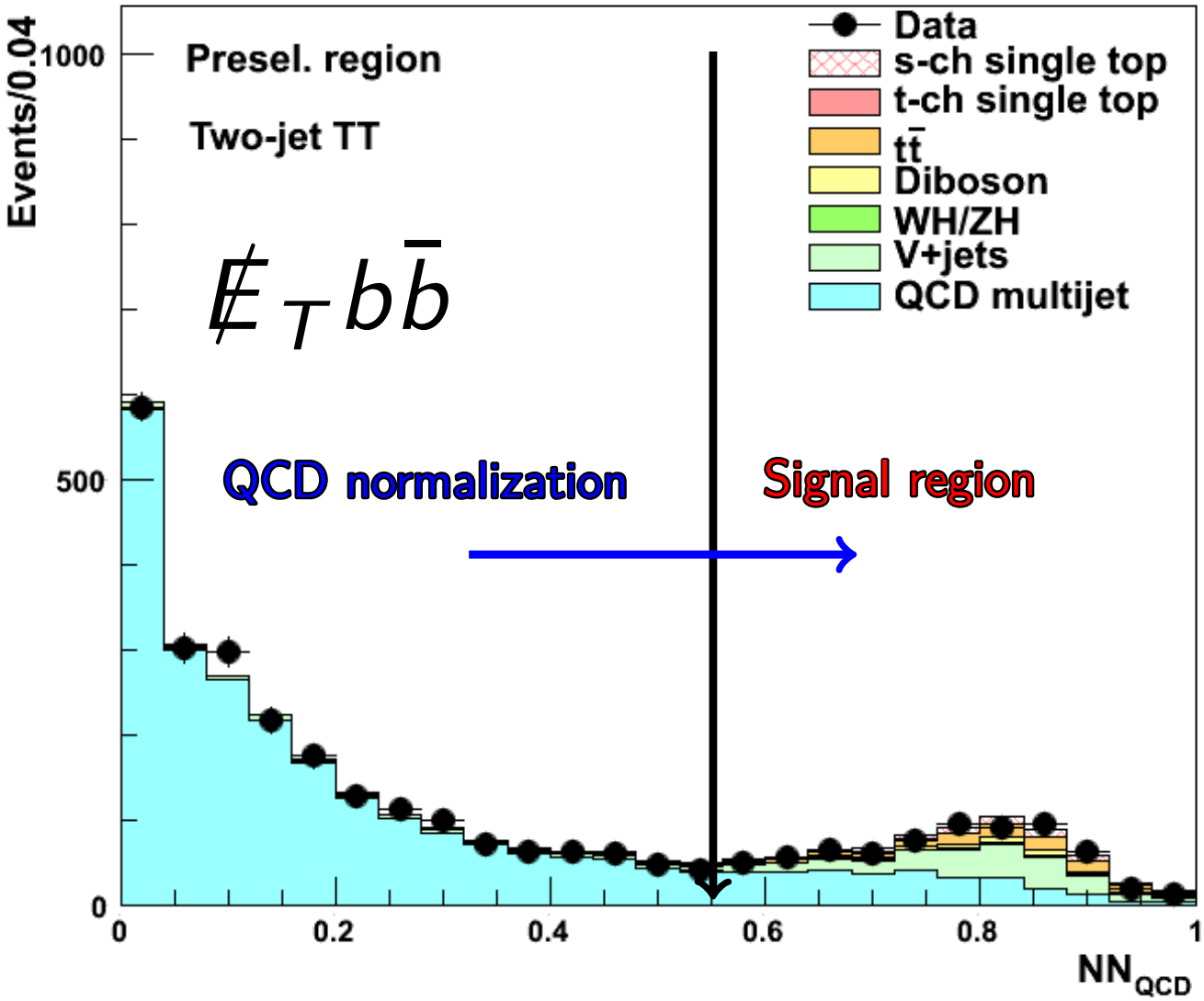
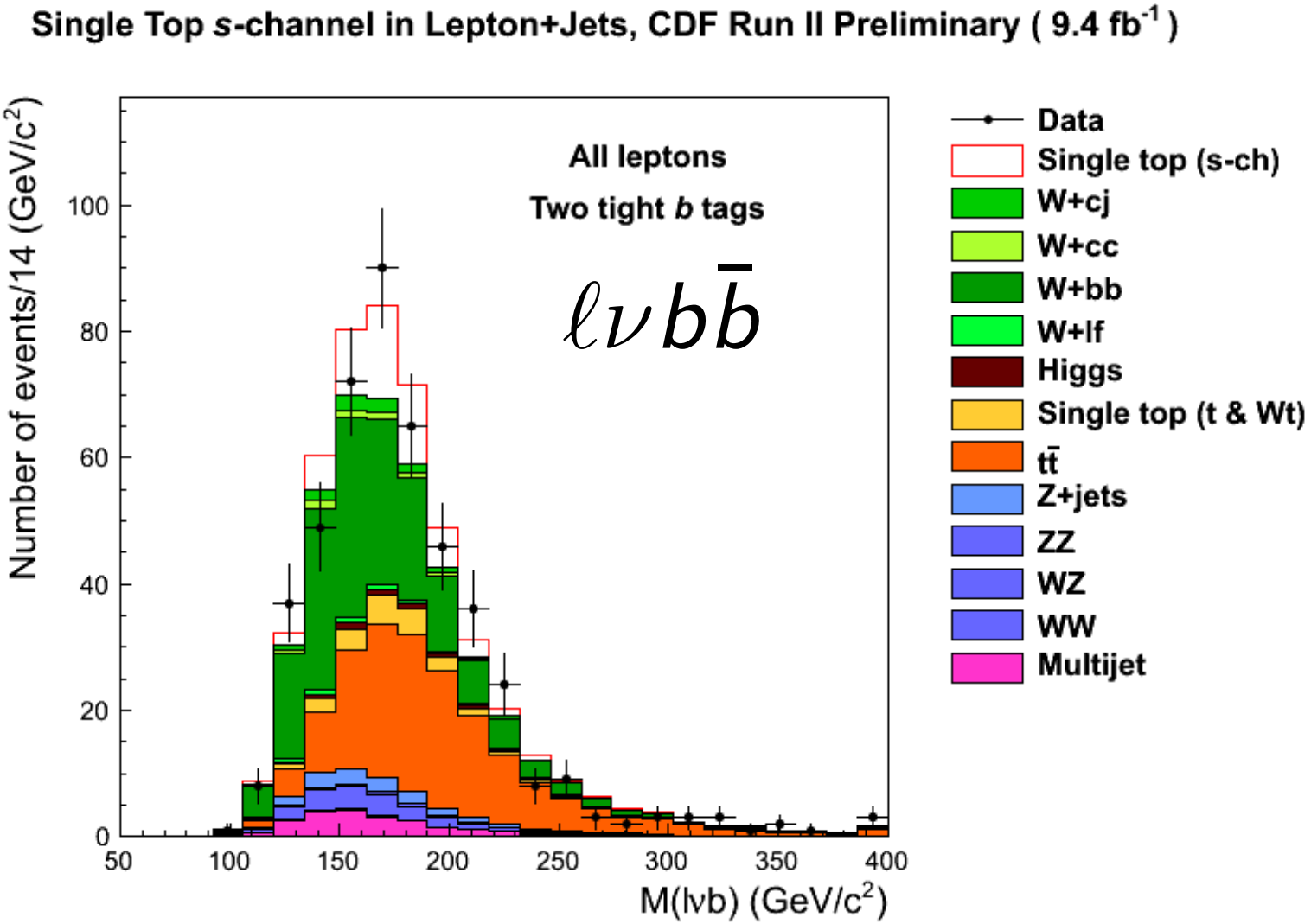


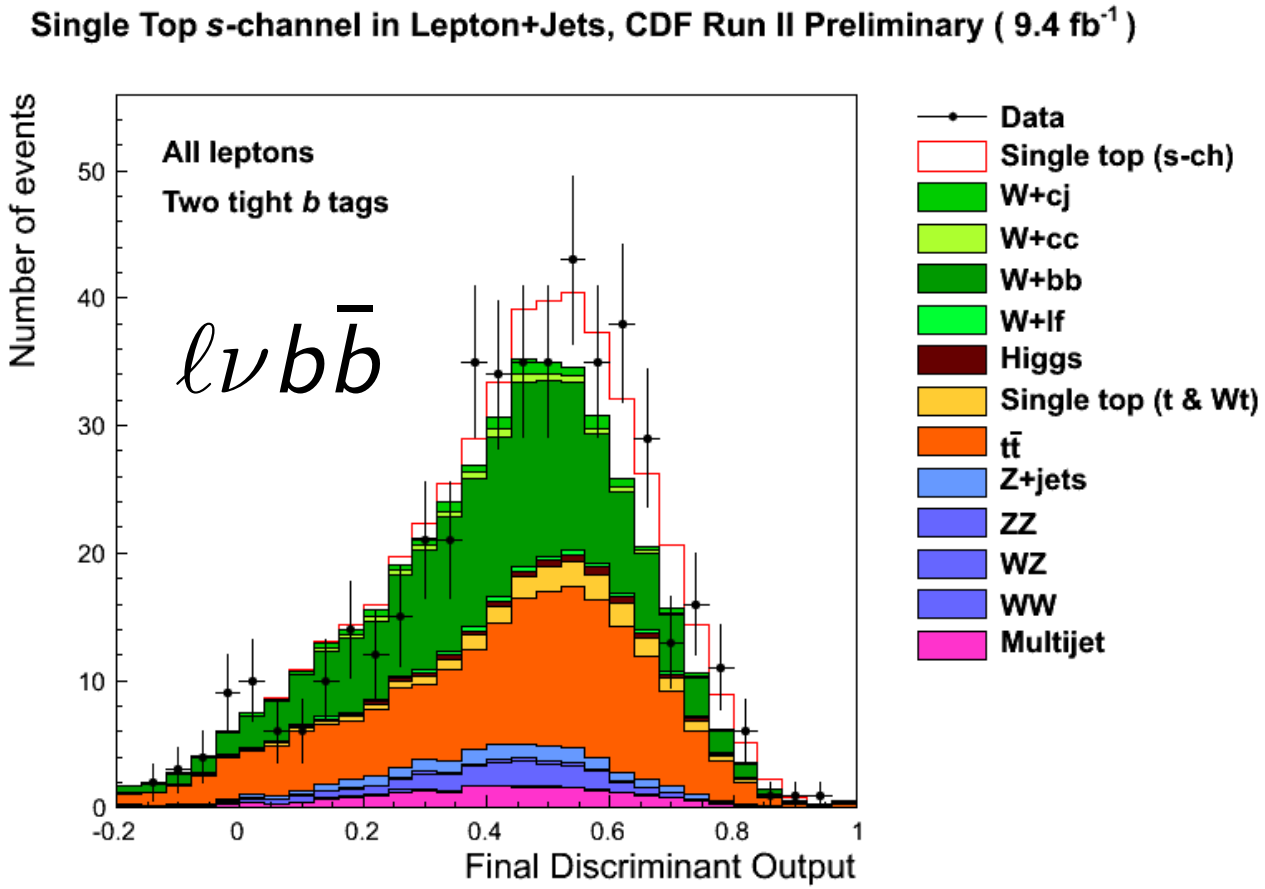
Top Quark Reconstruction

In both the CDF analyses, a neural network algorithm is employed to select the b jet which is originated from top quark.



Final Discriminant

- 10-20 kinematic variables are used in the training
- The training is optimized in each analysis subsample



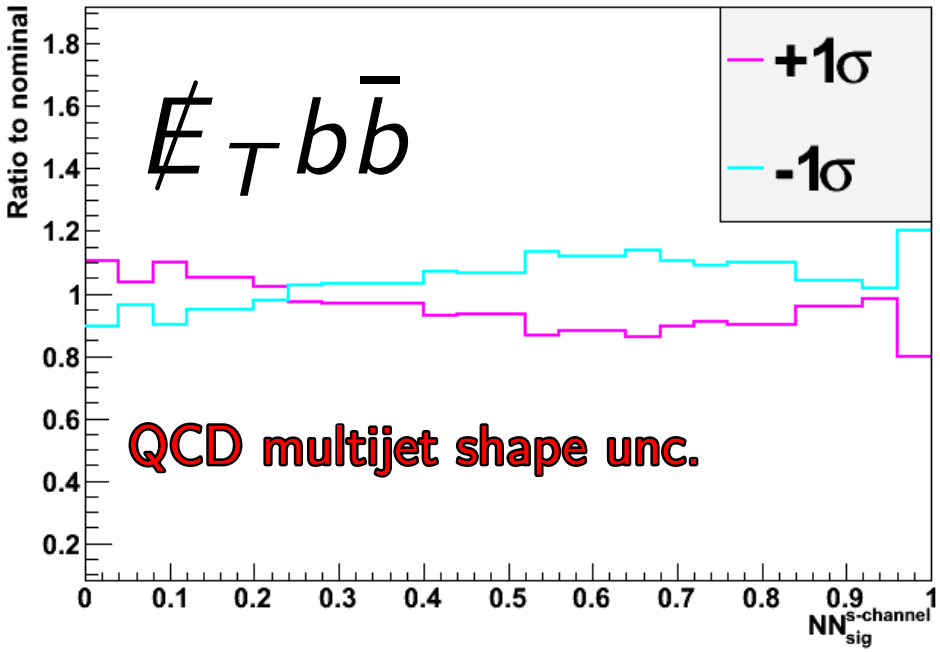
- Double-tag two-jet sample is the most sensitive
- Data clearly prefer the signal+background hypothesis

Cross Section Extraction

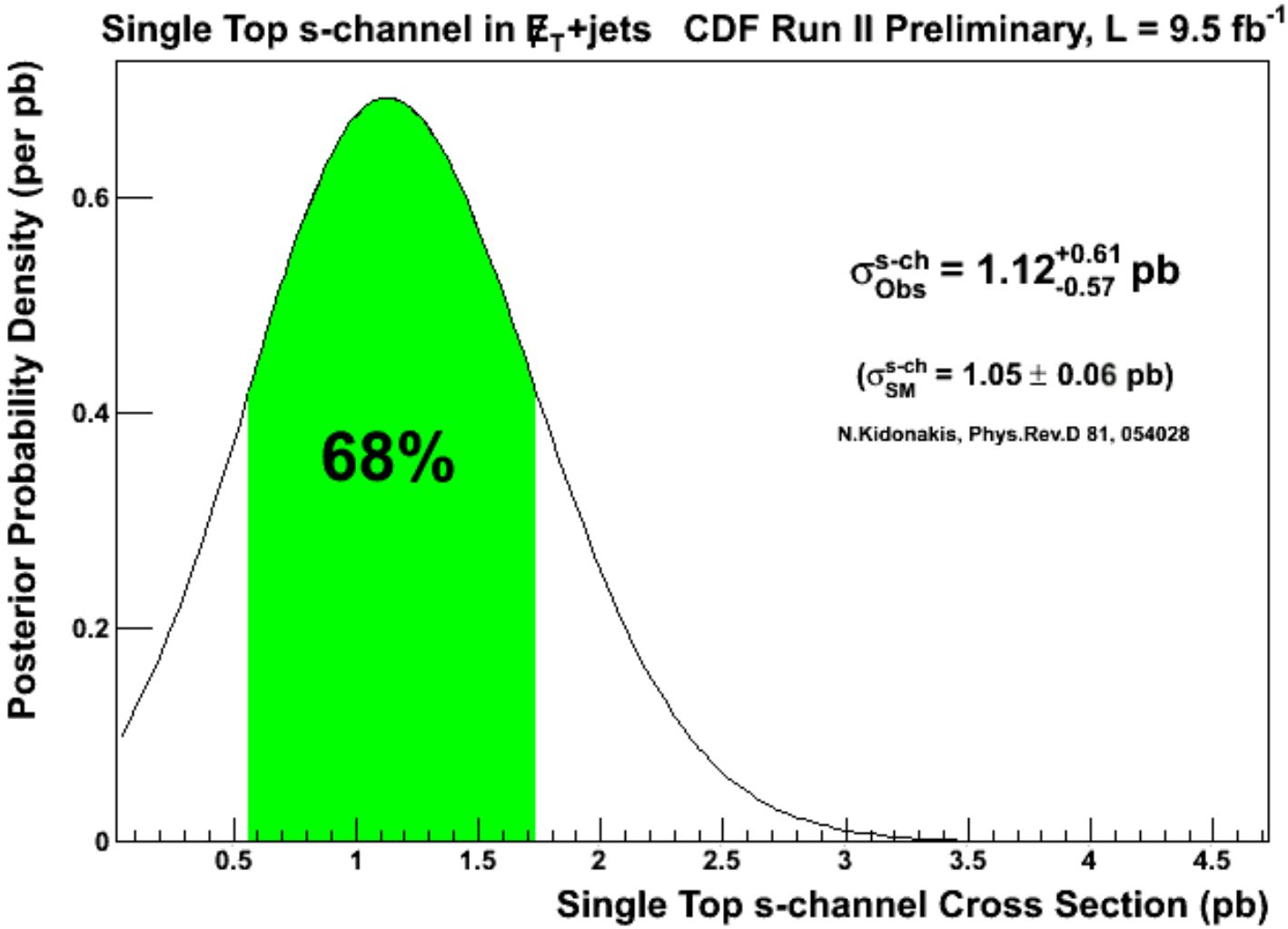
- ***t*-channel single top** and ***WH*/*ZH*** production included as backgrounds, constrained to the theoretical prediction
- Bayesian approach: likelihood fit to the binned final discriminant distribution
- Uniform, non-negative prior for signal cross section
- All the uncertainties on signal and background normalization and shape included

Systematic Uncertainties

- W+jets normalization uncertainty is the dominating one
- The **jet energy** is corrected separately for **quark** and **gluon** jets
  $\Rightarrow$ two different uncertainties
- A **shape uncertainty** on the **QCD multijet data-driven model** is included

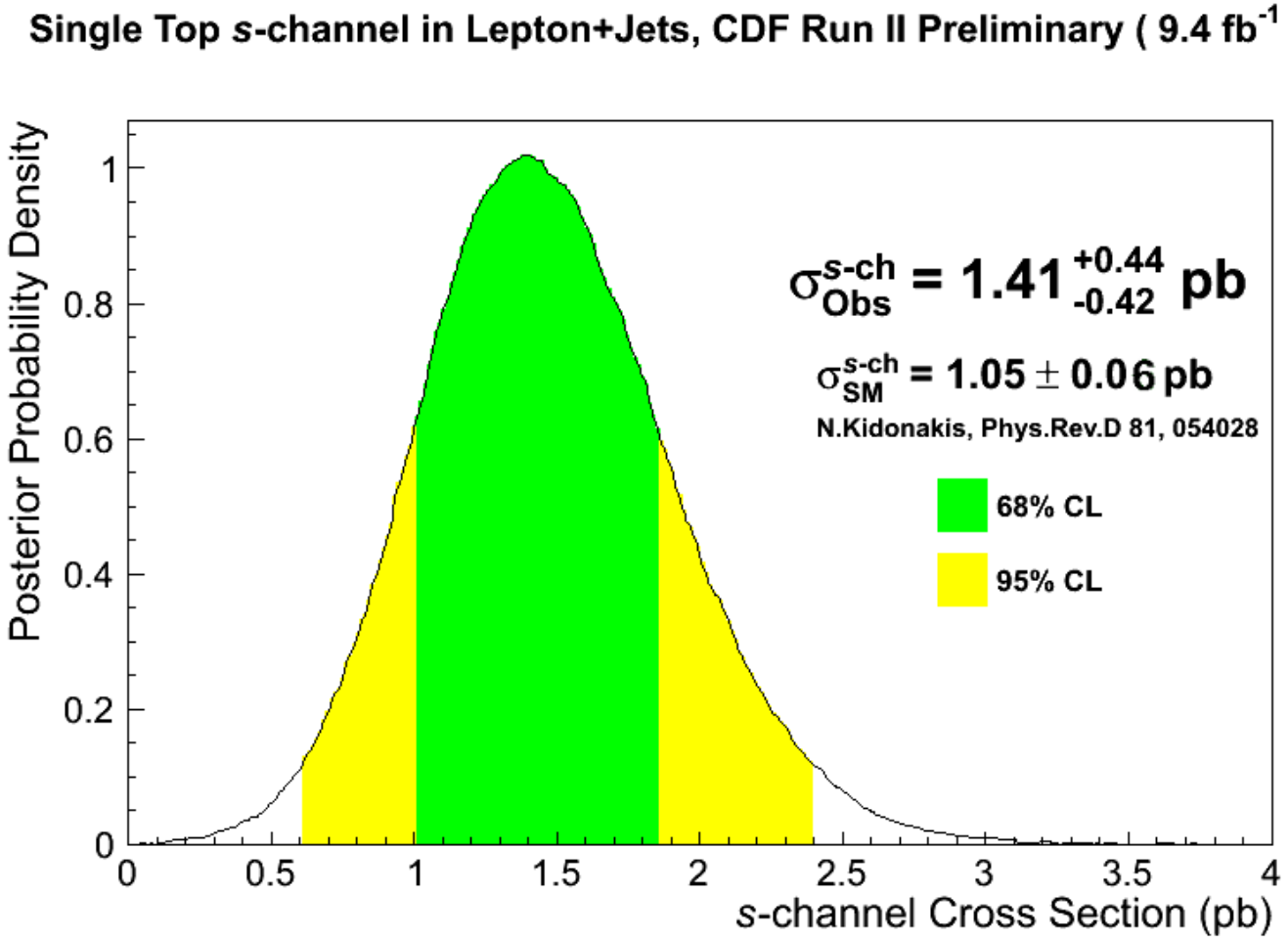


$\not\!\!E_T b\bar{b}$ Bayesian Statistical Analysis



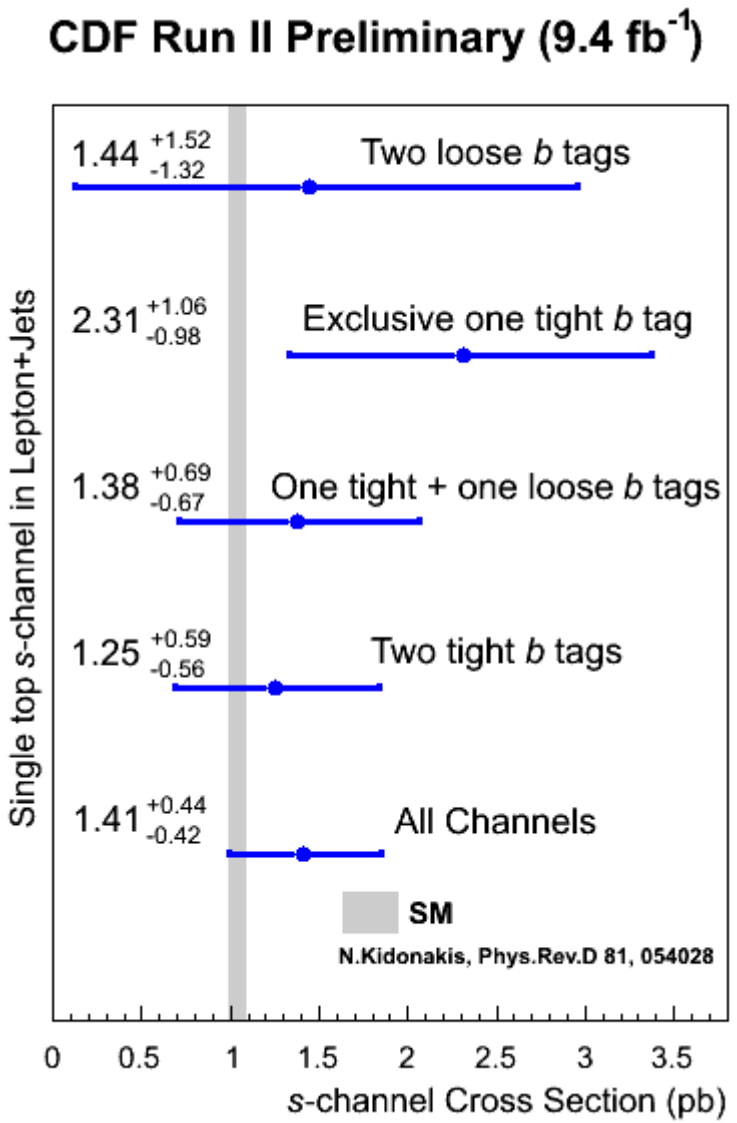
- Expected uncertainty: 57%
- Observed uncertainty: 53%

$\ell\nu b\bar{b}$ Bayesian Statistical Analysis



- Expected uncertainty: 38%
- Observed uncertainty: 30%

$\ell\nu b\bar{b}$ Consistency check

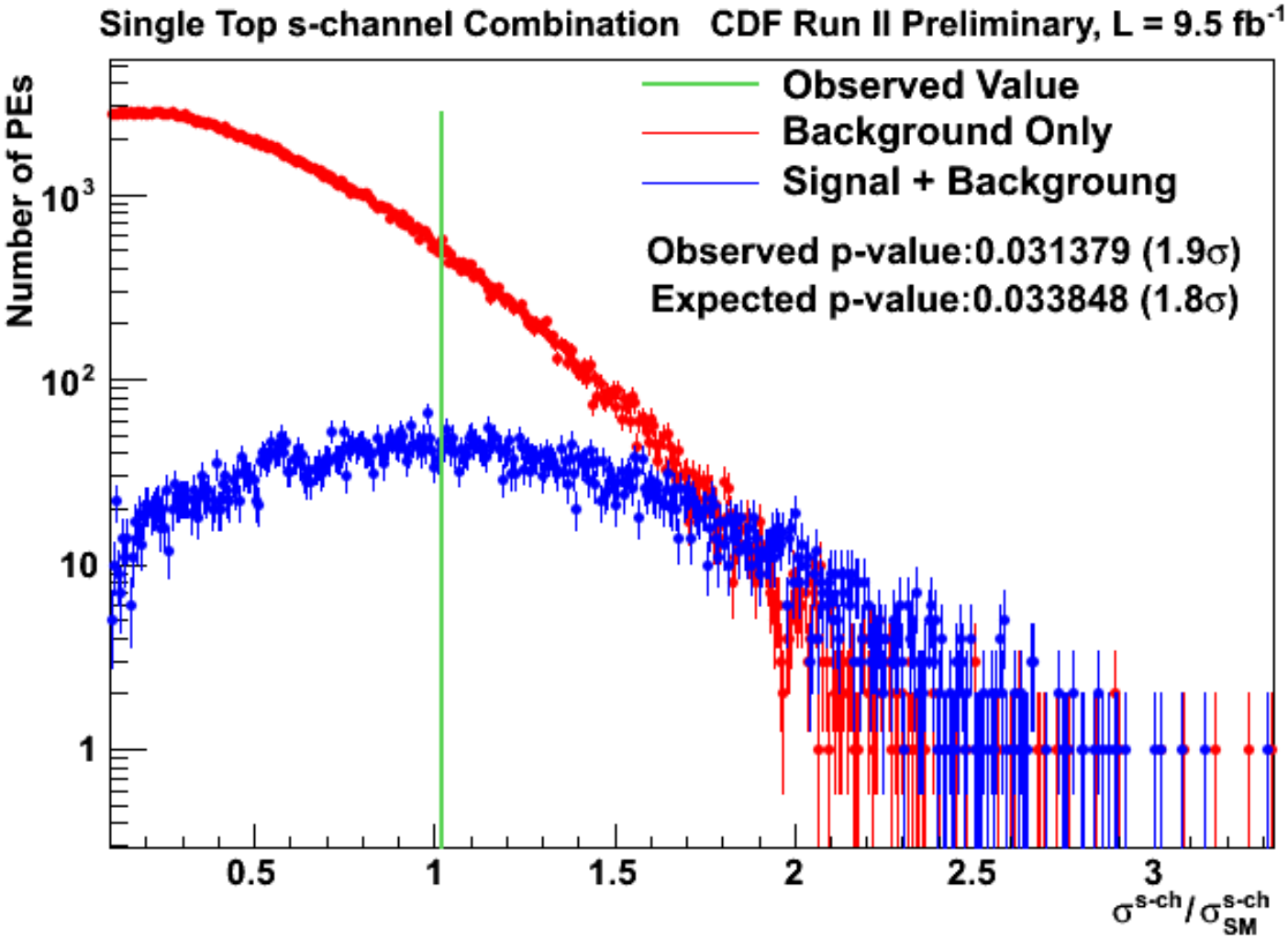


Measurements are consistent with each other in each subsample

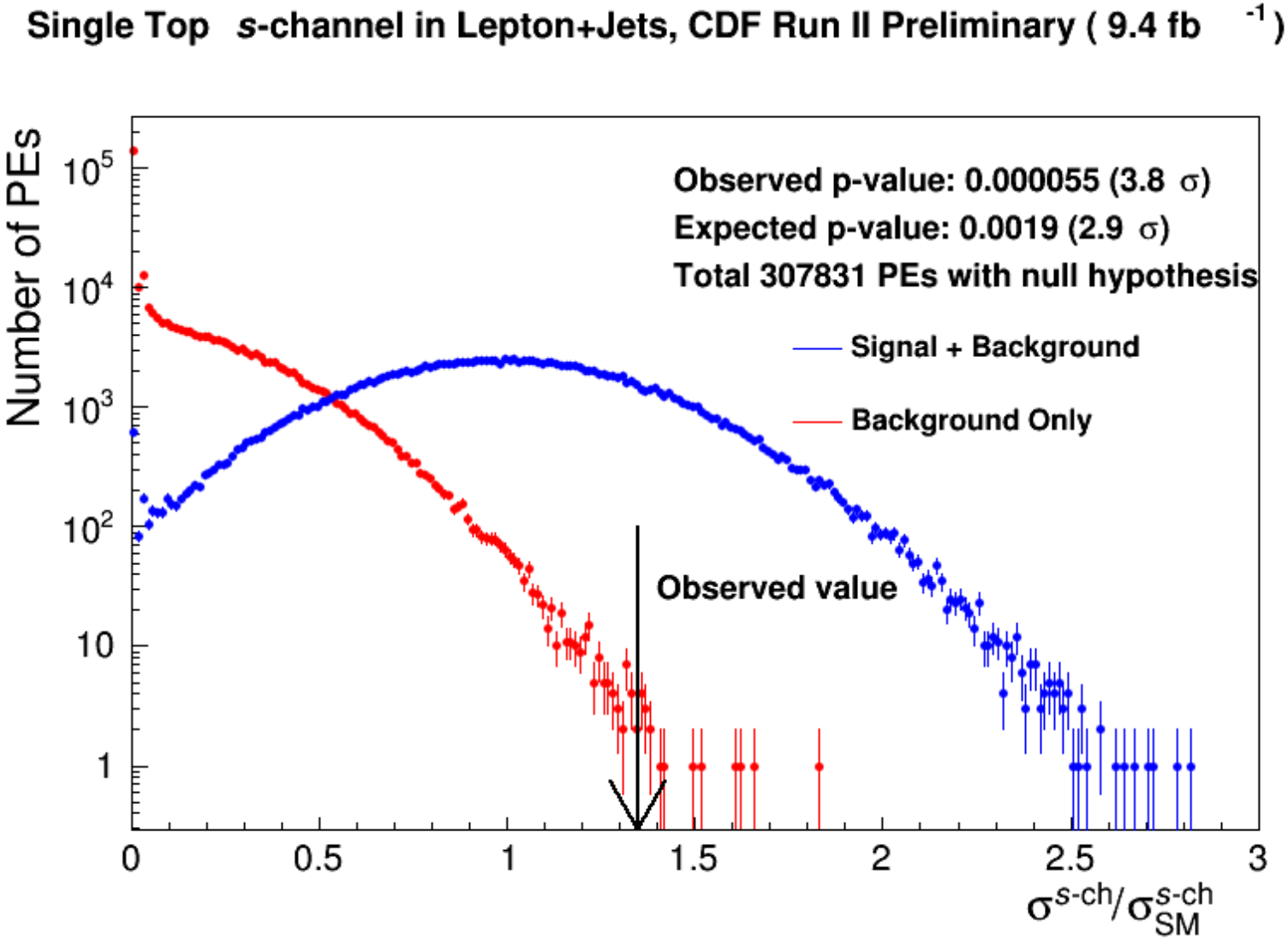
p-value Calculation

- The probability of observing a signal as large as the observed one or larger from fluctuation of the backgroud (**p-value**) is estimated
- The p-value is computed generating a large set of pseudoexperiment in signal+background and background-only hypothesis
- The expected p-value is calculated assuming a signal at the SM rate

$\not\!\!E_T b\bar{b}$ Significance



$\ell\nu b\bar{b}$ Significance

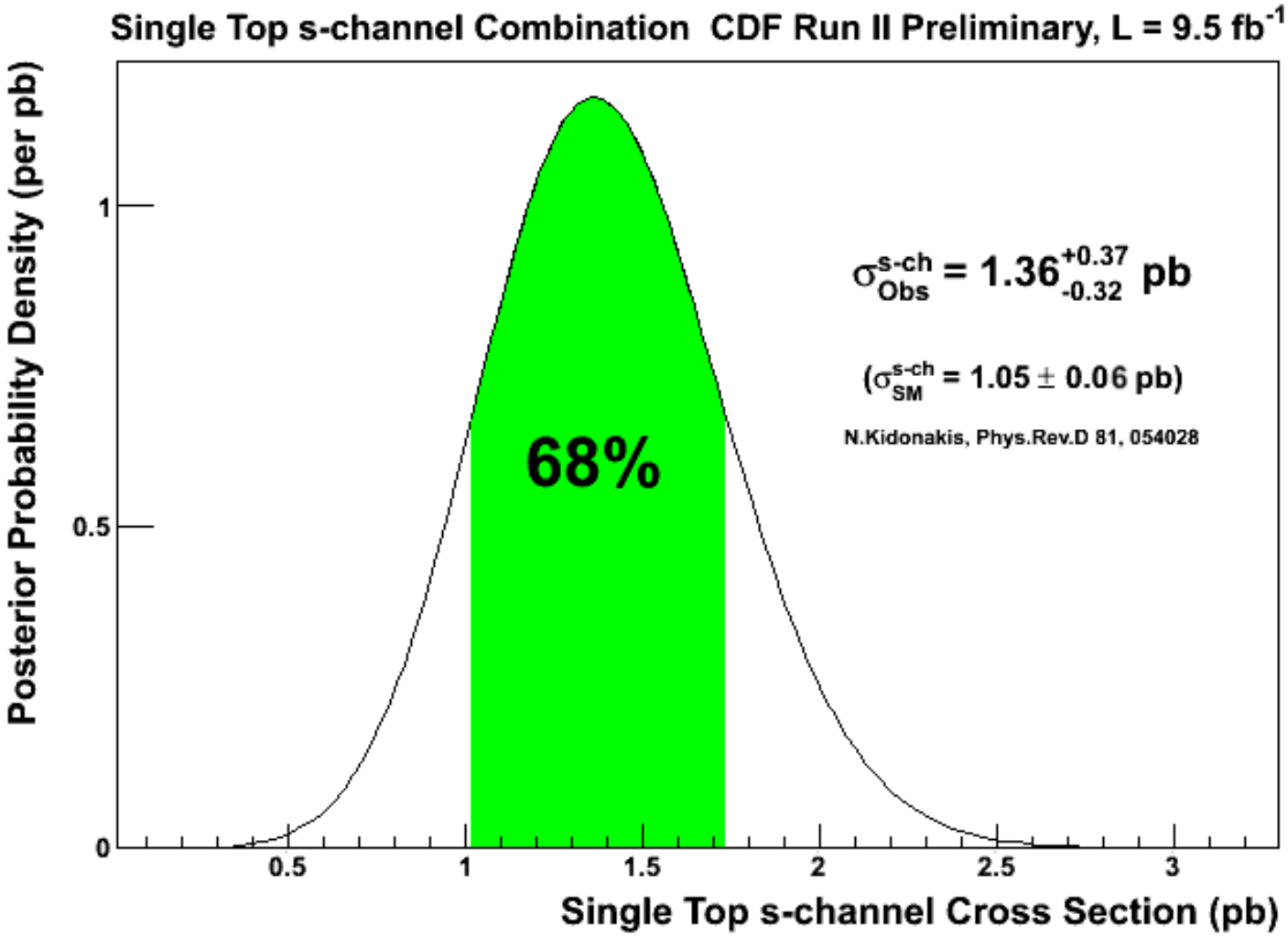


CDF Combination

CDF Combination Strategy

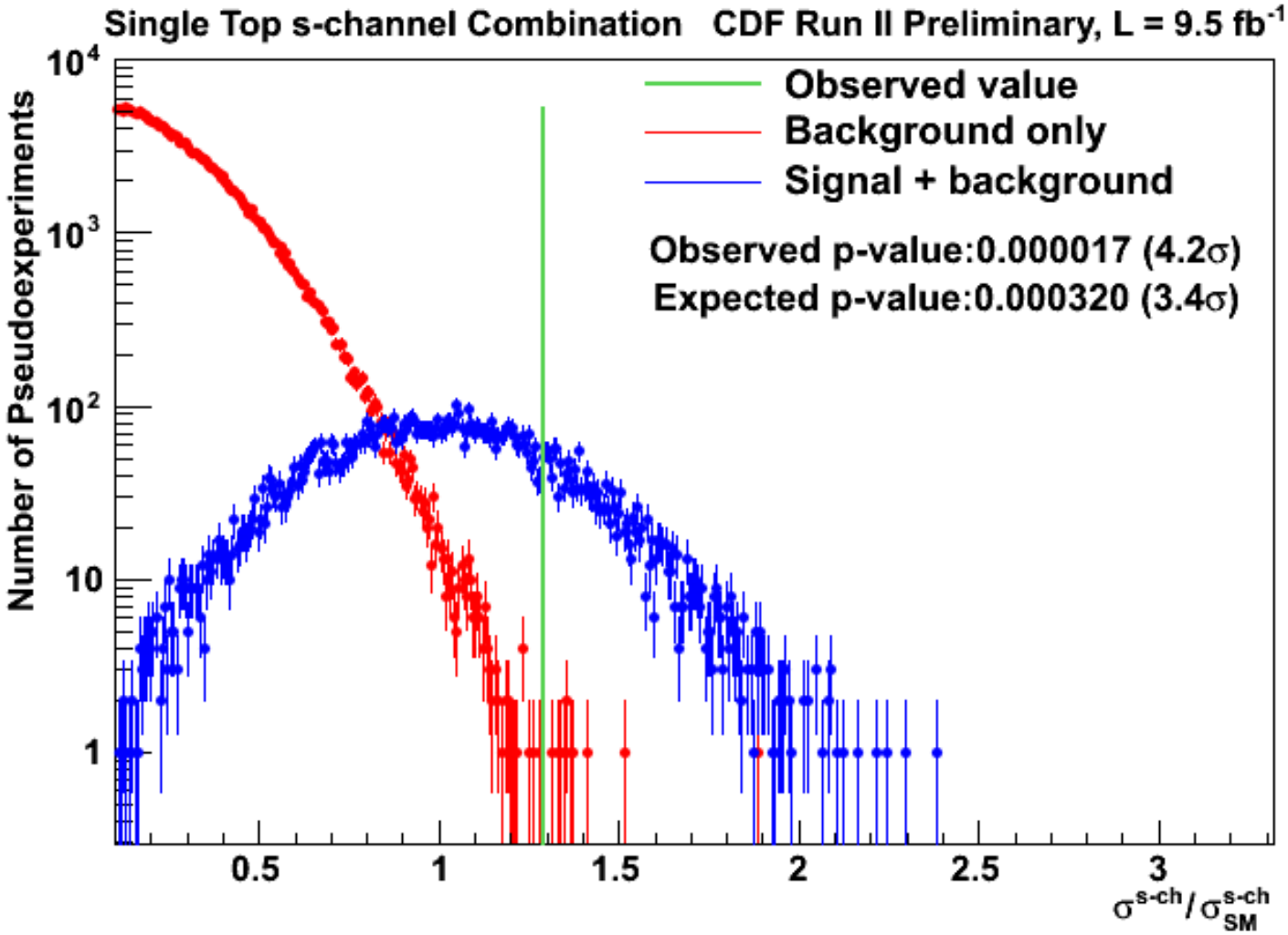
- Bayesian approach considering simultaneously all the subsamples from the $\ell\nu b\bar{b}$ and $\not\!\!E_T b\bar{b}$ analyses
- Use the same approach used in each single analysis to calculate significance
- All the uncertainties and their correlations taken into account

CDF Combined Bayesian Statistical Analysis



- Expected uncertainty: 33%
- Observed uncertainty: 25%

CDF Combined Significance

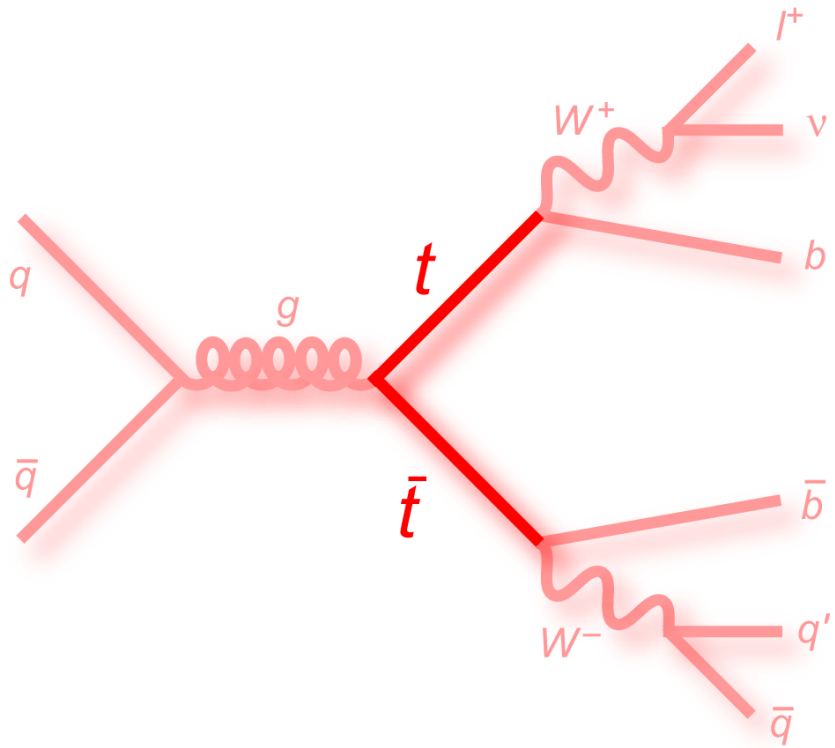


$t\bar{t}$ Pair Production

Top quark was discovered by CDF and D0 in 1995, in $t\bar{t}$ events

$\sigma_{t\bar{t}} \cong$ 7 pb; $S/B \cong 1$

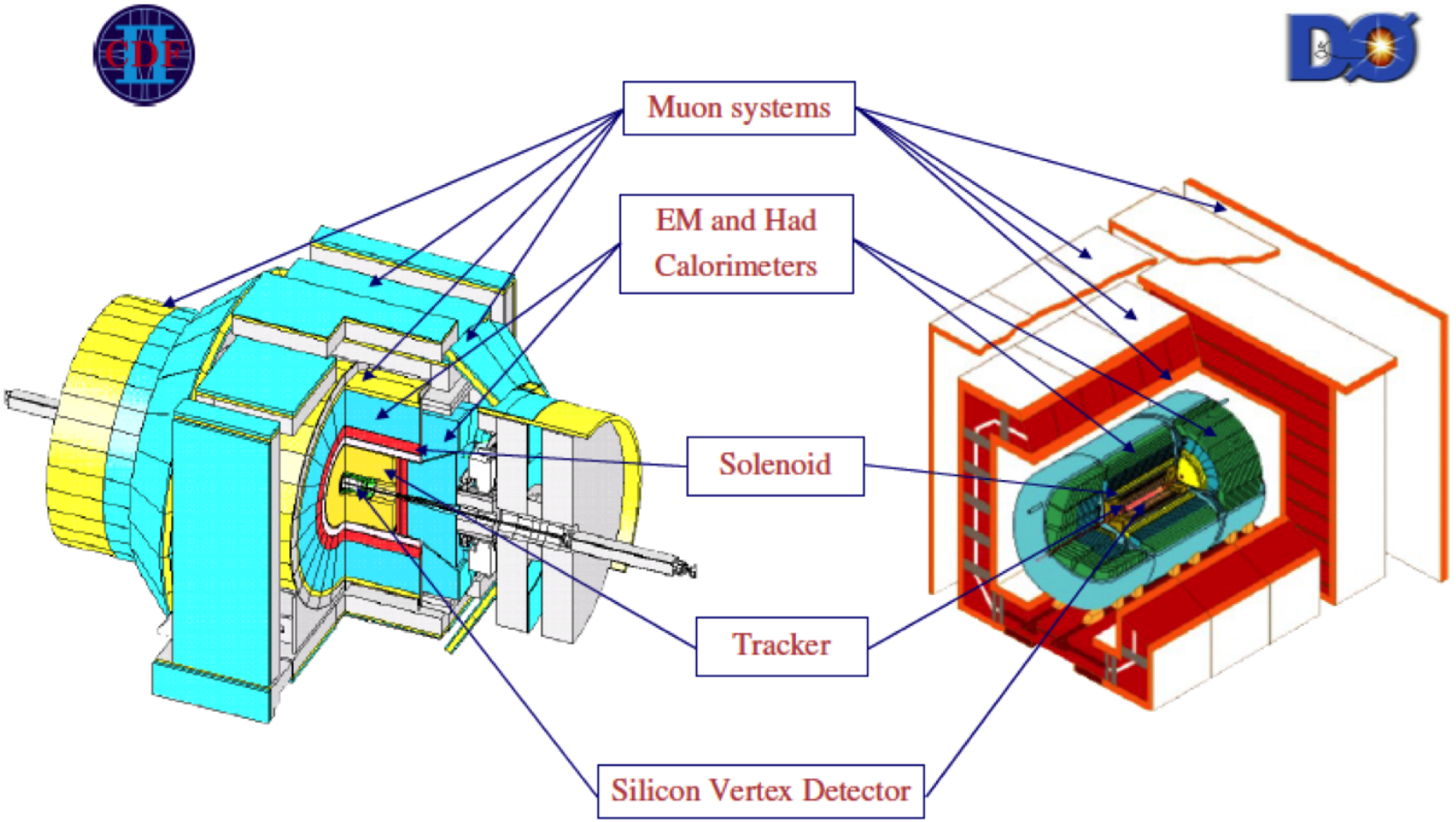
- The distinctive kinematic properties
- **Quite pure sample**
- Strong production easier to observe



The Tevatron

- Collider $p\bar{p}$ $\sqrt{s} = 1.96$ TeV
- Radius $R = 1$ km
- Two experiments: CDF and D0
- Run II (2001–2011):
  ~ 12 fb^{-1} of $p\bar{p}$ collisions,
  ~ 10 fb^{-1} recorded per experiment

The CDF and D0 Detectors



Analysis Challenges

Small signal, large background
$\Rightarrow$ Use a loose set of selection cuts, to preserve signal
$\Rightarrow$ Require b-tagged jets, to reduce background

Large background uncertainties:

- The main backgrounds are also the ones with the largest uncertainties

$\Rightarrow$ Carefully model signal and backgrounds

Poor separation $\Rightarrow$ Use multivariate techniques